GEOLOGY OF SOUTHEASTERN NEW ENGLAND
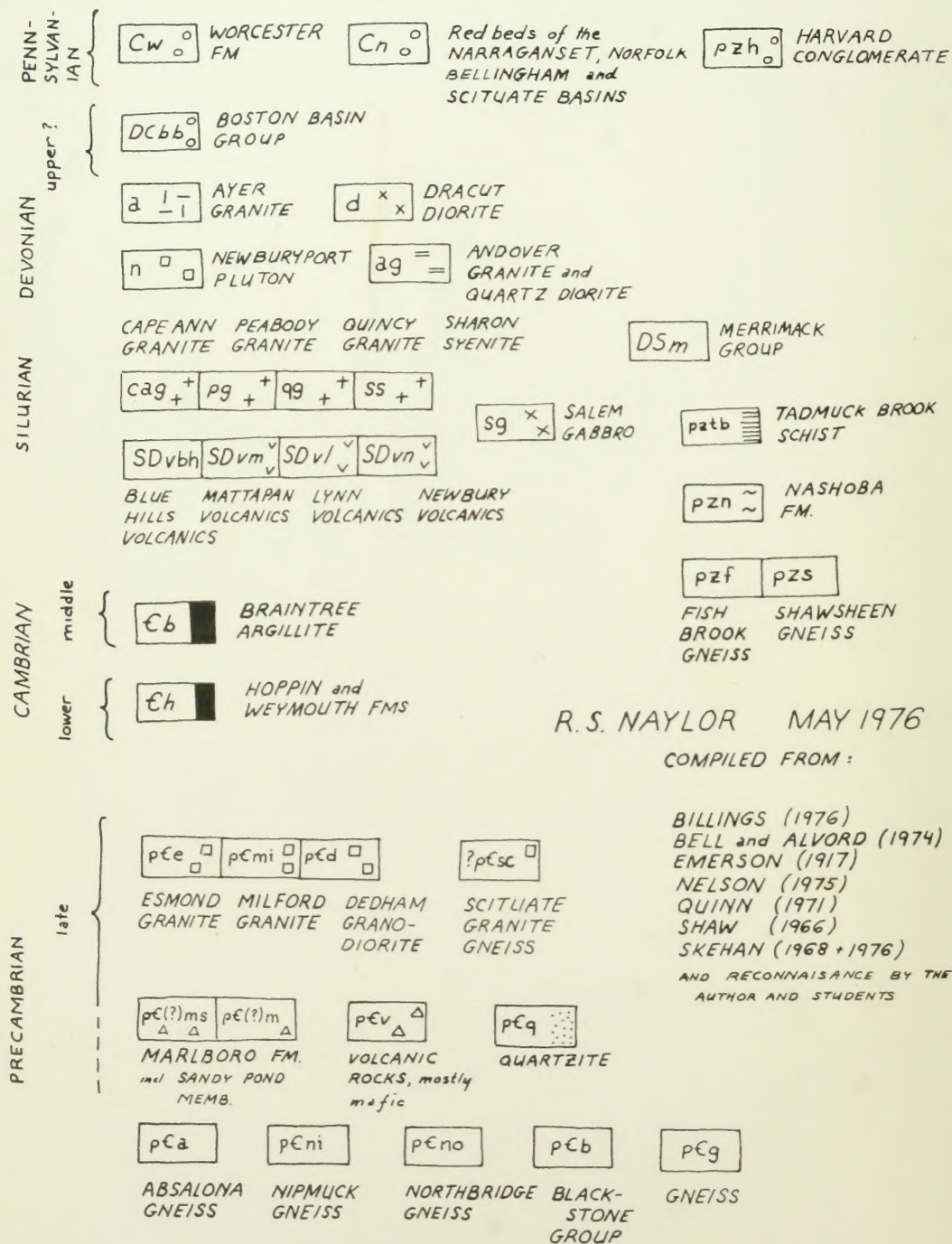
BOSTON

GENERALIZED BEDROCK GEOLOGIC MAP
EASTERN MASSACHUSSETS AND VICINITY

PENN-SYLVAN-IAN

| Cw | WORCESTER FM | Cn | Red beds of the NARRAGANSET, NORFOLK BELLINGHAM and SCITUATE BASINS | pzh | HARVARD CONGLOMERATE |

DEVONIAN — upper?

DCbb — BOSTON BASIN GROUP

a l-l — AYER GRANITE

d x x — DRACUT DIORITE

n — NEWBURYPORT PLUTON

ag = — ANDOVER GRANITE and QUARTZ DIORITE

CAPE ANN GRANITE   PEABODY GRANITE   QUINCY GRANITE   SHARON SYENITE

DSm — MERRIMACK GROUP

cag+   pg+   qg+   ss+

sg x — SALEM GABBRO

pztb — TADMUCK BROOK SCHIST

SILURIAN

SDvbh   SDvm   SDvl   SDvn

BLUE HILLS VOLCANICS   MATTAPAN VOLCANICS   LYNN VOLCANICS   NEWBURY VOLCANICS

pzn ~ — NASHOBA FM.

| pzf | pzs |

FISH BROOK GNEISS   SHAWSHEEN GNEISS

CAMBRIAN — middle

Cb — BRAINTREE ARGILLITE

CAMBRIAN — lower

Ch — HOPPIN and WEYMOUTH FMS

R. S. NAYLOR   MAY 1976

COMPILED FROM:

BILLINGS (1976)
BELL and ALVORD (1974)
EMERSON (1917)
NELSON (1975)
QUINN (1971)
SHAW (1966)
SKEHAN (1968 + 1976)
AND RECONNAISANCE BY THE AUTHOR AND STUDENTS

PRECAMBRIAN — late

| pCe | pCmi | pCd | | ?pCsc |

ESMOND GRANITE   MILFORD GRANITE   DEDHAM GRANO-DIORITE   SCITUATE GRANITE GNEISS

pC(?)ms   pC(?)m — MARLBORO FM. incl SANDY POND MEMB.

pCv — VOLCANIC ROCKS, mostly mafic

pCq — QUARTZITE

| pCa | pCni | pCno | pCb | pCg |

ABSALONA GNEISS   NIPMUCK GNEISS   NORTHBRIDGE GNEISS   BLACK-STONE GROUP   GNEISS

GEOLOGY OF SOUTHEASTERN NEW ENGLAND

A Guidebook for Field Trips

to the Boston Area and Vicinity

Edited by

Barry Cameron

Department of Geology
Boston University

68th Annual Meeting

NEW ENGLAND INTERCOLLEGIATE GEOLOGICAL CONFERENCE

October 8-10, 1976

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1976 NEIGC CONFERENCE ORGANIZATION

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PREFACE

In 1966, John Rodgers of Yale University, then Secretary of NEIGC, stated in the Mt. Katahdin, Maine, Guidebook that the New England Inter-collegiate Geological Conference, familiarly known as the "NEIGC", "... is perhaps the oldest continuous 'organization' on the continent whose sole aim is geological field trips. It began with an informal field trip in 1901, run by William Morris Davis in the Connecticut Valley of western Massachusetts, and gradually extended itself... over New England..." A few meetings have also been held outside of New England, in neighboring states and provinces, e. g., New York City, Montreal, Albany, and Fredericton, New Brunswick, (Fig. 1, Table 1). The continual success of NEIGC each year attests to the need for an informal field trip-oriented geological organization in the northeast. There is only one so-called member, the Secretary (presently "D" Caldwell, since 1967). One of his duties is to insure that there is a conference scheduled for each fall. Each year, then, a different group of hard-working local volunteers organizes a field conference and publishes a field trip Guidebook for the meeting. The purpose of NEIGC, therefore, is to arrange for field trips in areas where recent geological work has been done in order to bring together geologists interested in current problems in New England geology.

Field geologists generally shun urban areas. However, the Boston area and vicinity poses many perplexing geologic problems. Since the last Boston NEIGC meeting (1964), there has been much new work done in the area by geologists working for Universities, the U.S. Geological Survey, and other organizations. The purpose of the 1976 NEIGC is to provide field demon-strations of work recently completed or currently in progress in the Greater Boston Region. No single thematic approach was chosen for the conference because of the variety and complexity of the geology in this southeastern New England area. This Field Trip Guidebook has been printed not only for the benefit of the Conference participants who will have the personal guidance of the field trip leaders, but also for those geologists, teachers, students, and the interested public who, in the absence of personally guided tours by the field trip leaders, may wish to use the Guidebook to visit and study the geological features of the Greater Boston Area described herein.

During the late 1960's, "D" Caldwell and others suggested that Boston, with its varied and complex geology, would be an appropriate meeting place during the 1976 Bicentennial Year. In May, 1974, he gathered a small group of local geologists to form a steering committee to initiate plans for this conference. Smaller groups of geologists later worked on specific organi-zational tasks and, as the conference time approaches, more and more people have been "volunteering" to do all kinds of work!

It is with some anxiety that I write an acknowledgement to all of the people who helped with the NEIGC so far this year for fear that I will have forgotten someone deserving thanks. Without the extraordinary efforts of the 60 field trip leaders and guidebook authors listed herein this conference would not have been possible. My greatest personal gratitude and appreciation goes to Ms. China O. Ayer, who has helped me faithfully almost every day since

FIGURE I

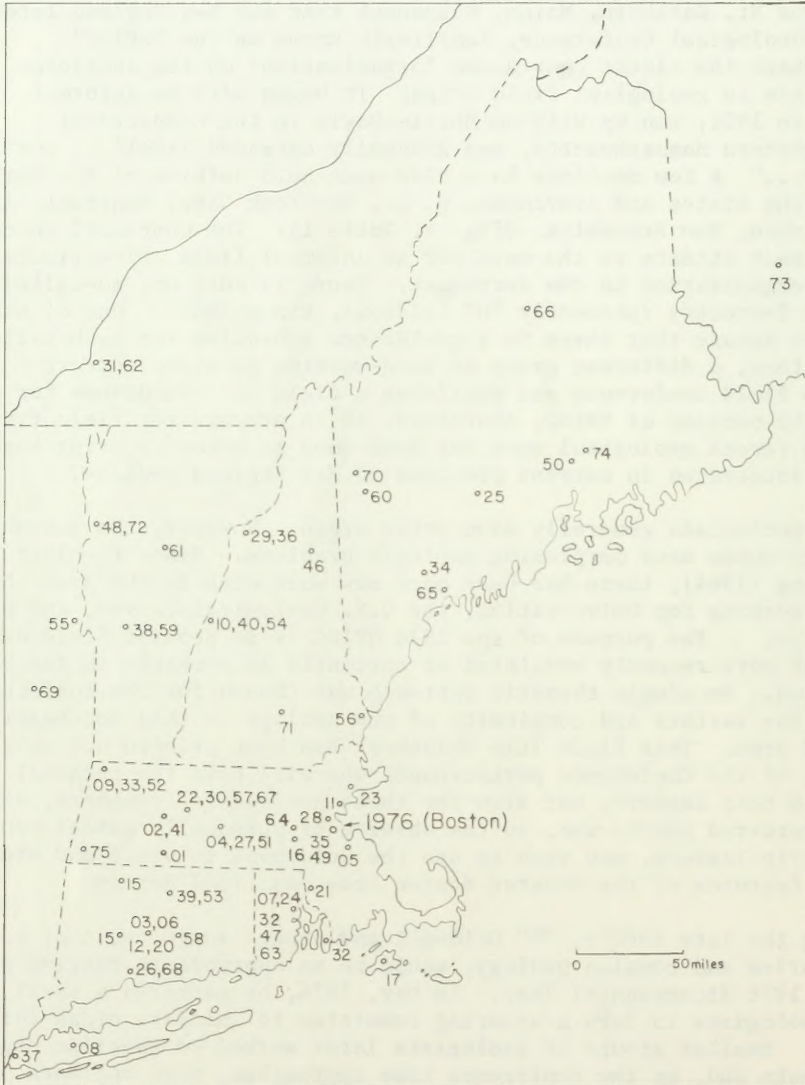NEW ENGLAND INTERCOLLEGIATE GEOLOGICAL CONFERENCE MEETING PLACES

Table 1.

CHRONOLOGICAL SUCCESSION OF MEETINGS OF THE

NEW ENGLAND INTERCOLLEGIATE GEOLOGICAL CONFERENCE

Meeting	Year	Place	Organizers
1.	1901	Westfield River Terrace, Mass.	Davis
2.	1902	Mount Tom, Mass.	Emerson
3.	1903	West Peak, Meriden, Conn.	Rice
4.	1904	Worcester, Mass.	Emerson
5.	1905	Boston Harbour & Nantasket	Johnson, Crosby
6.	1906	Meriden to East Berlin, Conn.	Gregory
7.	1907	Providence, R. I.	Brown
8.	1908	Long Island, N. Y.	Barrell
9.	1909	North Berkshires, Mass.	Cleland
10.	1910	Hanover, N. H.	Goldthwait
11.	1911	Nahant & Medford, Mass.	Lane, Johnson
12.	1912	Higby-Lamentation Blocks	Rice
13.	1915	Waterbury to Winsted, Conn.	Barrell
14.	1916	Blue Hills, Mass.	Crosby, Warren
15.	1917	Gay Head & Martha's Vineyard	Woodworth, Wigglesworth
16.	1920	Lamentation & Hanging Hills	Rice, Foye
17.	1921	Attleboro, Mass.	Woodworth
18.	1922	Amherst, Mass.	Antevs
19.	1923	Beverly, Mass.	Lane
20.	1924	Providence, R. I.	Brown
21.	1925	Waterville, Me.	Perkins
22.	1926	New Haven, Conn.	Longwell
23.	1927	Worcester, Mass.	Perry, Little, Gordon
24.	1928	Cambridge, Mass.	Billings, Bryan, Mather
25.	1929	Littleton, N. H.	Crosby
26.	1930	Amherst, Mass.	Loomis, Gordon
27.	1931	Montreal, Que.	O'Neill, Graham, Clark, Gill, Osborne, McGerrigle
28.	1932	Providence, R. I.	Brown
29.	1933	Williamstown, Mass.	Cleland, Perry, Knopf
30.	1934	Lewiston, Me.	Fisher, Perkins
31.	1935	Boston, Mass.	Morris, Pearsall, Whitehead
32.	1936	Littleton, N. H.	Billings, Hadley, Cleaves, Williams
33.	1937	New York City & Duchess Co.	O'Connell, Kay, Fluhr, Balk, Hubbert
34.	1938	Rutland, Vt.	Bain
35.	1939	Hartford & Conn. Valley	Troxell, Flint, Longwell, Peoples, Wheeler
36.	1940	Hanover, N. H.	Goldthwait, Denny, Stoiber, Shaub, Hadley, Bannerman
37.	1941	Northampton, Mass.	Balk, Jahns, Lochman, Shaub, Willard
38.	1946	Mt. Washington, N. H.	Billings
39.	1947	Providence, R. I.	Quinn
40.	1948	Burlington, Vt.	Doll

Table 1. (cont.)

Meeting	Year	Place	Organizers
41.	1949	Boston, Mass.	Nichols, Billings, Schrock, Currier, Stearns
42.	1950	Bangor, Me.	Trefethen, Raisz
43.	1951	Worcester, Mass.	Lougee, Little
44.	1952	Williamstown, Mass.	Perry, Foote, McFadyen, Ramsdell
45.	1953	Hartford, Conn.	Flint, Gates, Peoples, Cushman, Rodgers, Aitken, Troxell
46.	1954	Hanover, N. H.	Elston, Washburn, Lyons, McNair, McKinstry, Stoiber, Thompson
47.	1955	Ticonderoga, N. Y.	Rodgers, Walton, MacClintock, Bartolome
48.	1956	Portsmouth, N. H.	Novotny, Billings, Chapman, Bradley, Stewart, Freedman
49.	1957	Amherst, Mass.	Bain, Johannson, Rice, Stobbe, Woodland, Brophy, Webb, Kierstead, Shaub, Nelson
50.	1958	Middletown, Conn.	Rosenfield, Eaton, Sanders, Porter, Lungren, Rodgers
51.	1959	Rutland, Vt.	Zen
52.	1960	Rumford, Me.	Griscom, Milton
53.	1961	Montpelier, Vt.	Doll
54.	1962	Montreal, Que.	Clark
55.	1963	Providence, R. I.	Quinn
56.	1964	Chestnut Hill, Mass.	Skehan
57.	1965	Brunswick, Me.	Hussey
58.	1966	Katahdin, Me.	Caldwell
59.	1967	Amherst, Mass.	Robinson, Drake, Foose
60.	1968	New Haven, Conn.	Orville
61.	1969	Albany, N. Y.	Bird
62.	1970	Rangeley Lakes, Me.	Boone
63.	1971	Concord, N. H.	Lyons, Stewart
64.	1972	Burlington, Vt.	Doolan, Stanley
65.	1973	Fredericton, N. B.	Greiner
66.	1974	Orono, Me.	Osberg
67.	1975	Great Barrington, Mass.	Ratcliffe
68.	1976	Boston, Mass.	Cameron

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Dennis S. Wood	Geology, University of Illinois, Urbana

*F = Friday field trips, A = Saturday field trips, & B = Sunday field trips

GENERAL GEOLOGY OF SOUTHEASTERN NEW ENGLAND

By

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INTRODUCTION

The Greater Boston area of southeastern New England contains a great diversity of surficial and bedrock geology, reflecting an early complex tectonic history, later extensive glaciation, and recent topographic and geographic modifications by man. Southeastern New England lies within two geomorphic provinces: the New England Province to the northwest and the Atlantic Coastal Plain Province to the southeast. The Boston Basin, which extends out into Boston Harbor, is a topographic, sedimentary, and structural basin, surrounded by low hills dominated by late Precambrian to medial Paleozoic volcanics and intrusives (Fig. 1). To the north and west is the northeast-southwest trending Clinton-Newbury, Bloody Bluff fault zone containing a highly metamorphosed geosynclinal sequence cut by granites and diorites. Farther south, the Pennsylvanian Norfolk and Narragansett (coal-bearing) basins dominate the bedrock geology with granitic rocks outcropping to the east and west. To the southeast, the glacial moraines and outwash sediments of Cape Cod, Marthas Vineyard, and Nantucket Island dominate the surface geology (Fig. 1). North of Cape Cod the glacially derived sedimentary coast, with many sandy beaches, is often interrupted by bare, jagged rocks, especially north of Boston.

Despite the location here of an unusual concentration of active geology departments as well as an office of the United States Geological Survey, the geology of southeastern New England, especially eastern Massachusetts, is less well understood than that of most other areas in New England. The sedimentary rocks of the area are only sparsely fossiliferous with the result that the stratigraphic chronology of the region is based on only a handful of fossil localities. The problem of interpretation is further compounded by a lack of stratigraphic continuity that makes it difficult to trace units. The region has been invaded by intrusive rocks in which many of the older units appear as discontinuous pendants and xenoliths; faults abound, cutting the region into slices and blocks of small lateral extent; and finally, glacial cover is widespread, including moraines and extensive drumlin fields. Suspicion has grown over the last decade that some of the faults may be of great (although unknown) magnitude.

Important early references for the geology of the Boston area are L. LaForge's (1932) "Geology of the Boston Area, Massachusetts" and B. K. Emerson's (1917) "Geology of Massachusetts and Rhode Island." The most recent synthesis

Figure 1

GENERALIZED GEOLOGIC MAP OF
SOUTHEASTERN NEW ENGLAND

DOTS (•) REPRESENT CITIES ON FIGURE 2
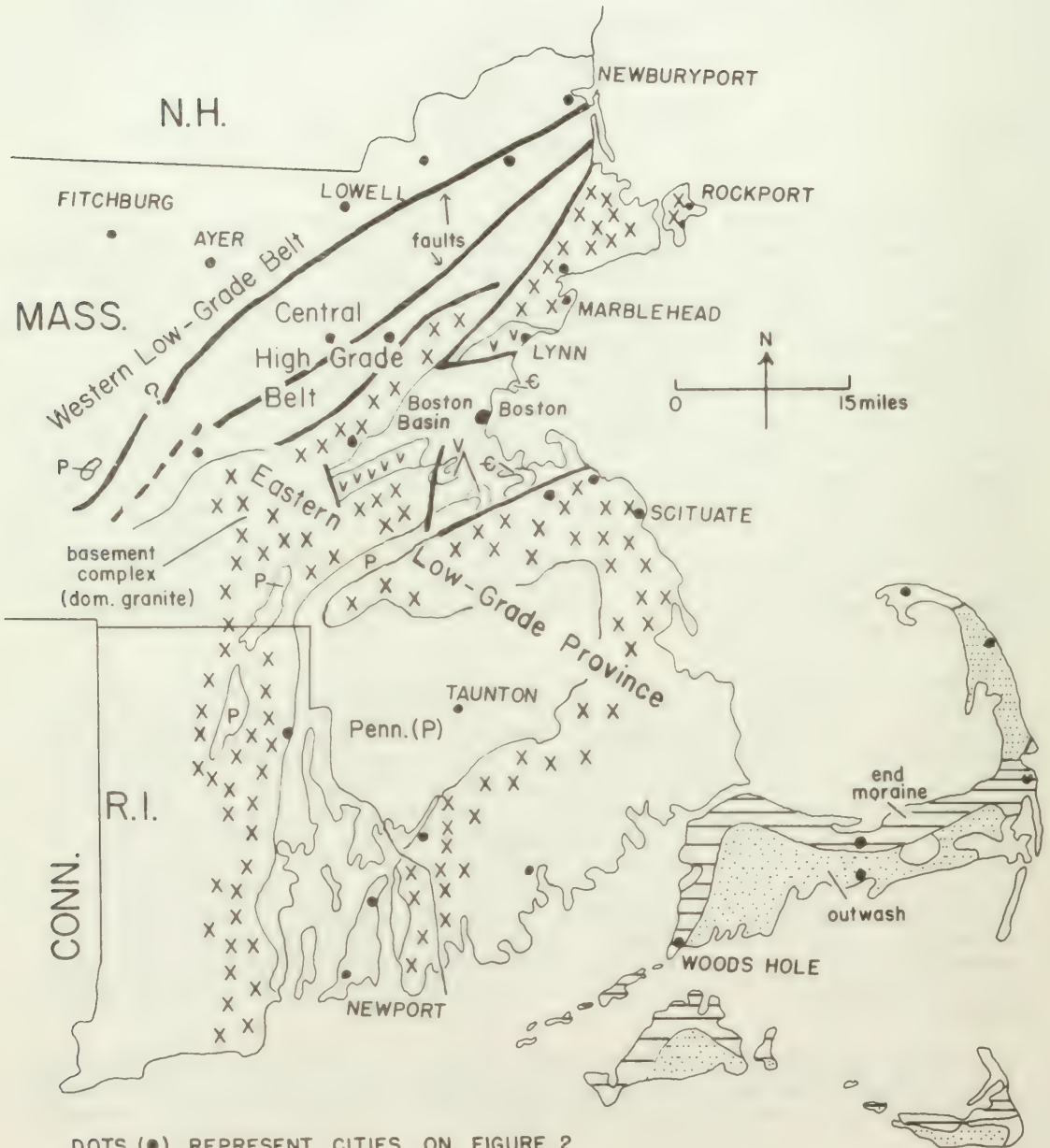
Figure 2

GENERALIZED FIELD TRIP LOCALITY MAP

N.H.

NEWBURYPORT • A8,B8
A16,B16 PLUM
IS

LAWRENCE •
GEORGETOWN • CAPE ANN
ROCKPORT •
• LOWELL A11,B11 • GLOUCESTER

FITCHBURG •
AYER •
A15,B15
• BEVERLY
F4 A17 STONEHAM • MARBLEHEAD
A14,B14 CONCORD • WOBURN • B12
F3 • LEXINGTON • LYNN
• CLINTON B7 • MEDFORD
A13 CAMBRIDGE A9 BOSTON
F5 A1,B1 BAY
B5 A5 • BOSTON
A2,B2 A6,B6 A9,B9
A12 WESTBORO • WELLESLEY F1 • QUINCY • NANTASKET
• WORCESTER B19 A3,B3 • COHASSET
F2 DEDHAM • BRAINTREE A4,B4
WEYMOUTH SCITUATE

B13 MASS. F7

• WEBSTER
A7
• BRIDGEWATER • PLYMOUTH PROVINCETOWN

B18 • TRURO
• ATTLEBORO
CAPE COD
• TAUNTON
CAPE COD
BAY A10,B10
PROVIDENCE • ORLEANS

N
0 15mi

RHODE • FALL RIVER
ISLAND BARNSTABLE
NEW • HYANNIS
F6 • BEDFORD
• PORTSMOUTH

CONN.
A18 B17
NEWPORT • WOODS
HOLE
MARTHA'S
VINEYARD

NANTUCKET

jrj

15

of the bedrock and surficial geology of the Boston Basin are by Billings (1976 and this volume) and Kaye (this volume), respectively. Recently, J. W. Skehan, S. J., (1975) prepared a geologic field guide for historic trails of Boston which contains excellent maps, a mileage log, and descriptions of many outcrops in the Boston area. In July, 1976, the "Wolfe Volume" ("Studies in New England Geology," edited by P. C. Lyons and A. H. Brownlow) will be published as GSA Memoir 146 in honor of Professor C. Wroe Wolfe (trip leader herein for trips F-1 and B-12). It contains seven papers on the Geology of eastern Massachusetts. LaForge's Bulletin (1932) contains J. F. and S. L. Dana's earliest (1818) geologic map of the Boston area, as well as a generalized geologic map of southeastern New England, a map of drumlins and eskers in the Boston area, and two large scale maps (in pocket) of the bedrock and surficial geology of the Boston and Boston Bay quadrangles. Although there have been many reports since Emerson's (1917) preliminary geologic map of Massachusetts and Rhode Island, this work is still a standard reference noted for its fine stratigraphy and is not to be ignored by anyone planning to study New England geology. Most of the fossil localities were known to Emerson and few significant discoveries have been made since then. However, his age assingments have been considerably revised, based partly on improved understanding of field relationships within the area, partly on correla- tions with areas along strike, and partly on radiometric dating. Unfortunately, these revisions have been made piecemeal, with the result that some units retain their conventional dates despite the fact that the arguments on which the original assignments were based may no longer be credible.

We have attempted a preliminary regional synthesis in the process of compiling this article and the accompanying map (cover and Fig. 3) for an introduction to the Field Trip Guidebook for the 1976 Boston meeting of the New England Intercollegiate Geological Conference. The reader will note that different ages are assigned to certain units by the authors of the various trips (Fig. 2) and can rest assured that the "final word" on the geology of eastern Massachusetts and vicinity has yet to be writ.

GEOLOGY OF THE EASTERN LOW-GRADE PROVINCE

Introduction:

The wide belt of rocks in eastern Massachusetts southeast of the Bloody Bluff Fault (Fig. 1) is characterized by regional metamorphism of greenschist or lower facies, except for a zone of high-grade (kyanite-staurolite) post-Pennsylvanian metamorphism in southern Rhode Island (trips F-6, A-18, B-17). Contact metamor- phism occurs near many igneous bodies. Certain rock units occurring in this belt possibly reappear at higher grade immediately west of the Bloody Bluff Fault. Included in this region are (1) the Boston Basin sedimentary and volcanic rocks whose age is in debate, (2) the Paleozoic rhyolitic extrusives along the northern and southern margins of this basin, (3) the Precambrian and Paleozoic intrusive rocks surrounding the Boston area, (4) the Cambrian sedimentary rocks along the eastern and southeastern margins of the Boston Basin, and (5) the four Pennsylva- nian basins in southeastern Massachusetts and Rhode Island (Norfolk, Narragansett, Woonsocket, and North Scituate basins) (Fig. 4).

Precambrian Terrane:

Late Precambrian rocks are widespread in southeastern Massachusetts and adjacent Rhode Island (Fig. 3). Billings (1929) concluded that the Early Cambrian Hoppin Formation in the northwestern Narragansett Basin (at Hoppin Hill near Attleboro) rests non-conformably on granite, a relationship virtually requiring that the granite be Precambrian. From this observation he argued that the widespread Dedham Granodiorite (trips A-4 & B-4) and related units were also Precambrian. This correlation was somewhat daring and not universally accepted, inasmuch as the rock types are not identical and the Hoppin Hill locality is completely surrounded by Pennsylvanian strata, but it has subsequently been confirmed by isotopic dating. Fairbairn and others (1967) report Rb-Sr whole-rock ages of 514 ± 17 m. y. for the granite at Hoppin Hill, 591 ± 28 m. y. for the Westwood Granite (mapped with the Dedham Granodiorite), and 569 ± 4 m. y. for the Northbridge Gneiss. These ages appear to have been lowered somewhat by later disturbance because they are slightly young for Late Precambrian on current time-scales. (This problem affects many Rb-Sr ages along the eastern margin of the Appalachians.) Zartman and Naylor (1972 & in preparation) report an Rb-Sr age of 614 ± 24 m. y. for carefully selected, fresh samples of Milford Granite and a zircon $^{207}Pb/^{206}Pb$ age of 630 m. y. from one sample of Milford Granite. ($^{87}Rb = 1.39 \times 10^{-11}$ year^{-1}.) These data suggest that the widespread Dedham Granodiorite and Milford Granite, and probably the Esmond Granite of Rhode Island, are Late Precambrian intrusive rocks.

The same terrane contains abundant volcanic rocks, ranging from basalt to rhyolite, that are only slightly metamorphosed southeast of the Bloody Bluff Fault (greenschist facies) (trip A-17). West of the fault similar rocks appear at higher grade as amphibolites and fine-grained felsic gneisses. Closely associated with these rocks are fine-grained quartzites, some of which may have originated as chert interbedded with the volcanics. Some exposures of quartzite are xenoliths or roof-pendants cut by the Milford Granite, but clear cross-cutting relationships between the dated occurrences of Dedham and Milford and the volcanics have not been proven. The overall impression is of a widespread Late Precambrian calc-alkaline volcanic terrane cut by related magmas. The mineralogy and field relationships suggest a moderate degree of unroofing, amounting to perhaps several kilometers. Except for what appears to be a greater degree of unroofing in Massachusetts, the province correlates with similar terranes on the Avalon Penninsula, Newfoundland, on Cape Breton Island, Nova Scotia, and on the New Brusnwick coast near St. John. By analogy with similar (but younger) rocks in the Oliverian Domes on New Hampshire, it seems possible that much of the Northbridge Gneiss may be metamorphosed, Late Precambrian quartz-dacite volcanics related to the other volcanics.

Although not yet isotopically dated, it is possible that some bodies of gneiss and metasediment may be older than the rocks mentioned above. Parts of the Blackstone Series, the Nipmuck Gneiss, and the Absalona and related gneisses fall into this catagory. It is not yet established whether they constitute a basement to the volcanics and calc-alkaline intrusives or whether they are structurally intercalated by faulting, if indeed they prove to be older.

Cambrian Rocks:

Early Cambrian fossils have been identified in the Hoppin Formation (quartzite, carbonate, and slate) and in the Weymouth Formation (shale and carbonate) (trips A-4 & B-4) and Middle Cambrian fossils occur in the Braintree Argillite (Fig. 3) (trips A-4 & B-4, A-3 & B-3). Upper Cambrian fossils are

GENERALIZED BEDROCK GEOLOGIC MAP
EASTERN MASSACHUSSETS and VICINITY

PENNSYLVANIAN

- Cw — WORCESTER FM
- Cn — Red beds of the NARRAGANSET, NORFOLK, BELLINGHAM and SCITUATE BASINS
- pzh — HARVARD CONGLOMERATE

DEVONIAN

upper ?

- DCbb — BOSTON BASIN GROUP
- a — AYER GRANITE
- d — DRACUT DIORITE
- n — NEWBURYPORT PLUTON
- ag — ANDOVER GRANITE and QUARTZ DIORITE

SILURIAN

- CAPE ANN GRANITE / PEABODY GRANITE / QUINCY GRANITE / SHARON SYENITE
- DSm — MERRIMACK GROUP
- cag / pg / qg / ss
- sg — SALEM GABBRO
- patb — TADMUCK BROOK SCHIST
- SDvbh / SDvm / SDvl / SDvn
- BLUE HILLS VOLCANICS / MATTAPAN VOLCANICS / LYNN VOLCANICS / NEWBURY VOLCANICS
- pzn — NASHOBA FM.

CAMBRIAN

middle

- Cb — BRAINTREE ARGILLITE
- pzf — FISH BROOK GNEISS
- pzs — SHAWSHEEN GNEISS

lower

- Ch — HOPPIN and WEYMOUTH FMS

R. S. NAYLOR   MAY 1976

COMPILED FROM:

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BELL and ALVORD (1974)
EMERSON (1917)
NELSON (1975)
QUINN (1971)
SHAW (1966)
SKEHAN (1968 + 1976)
AND RECONNAISANCE BY THE AUTHOR AND STUDENTS

PRECAMBRIAN

late

- pCe — ESMOND GRANITE
- pCmi — MILFORD GRANITE
- pCd — DEDHAM GRANODIORITE
- ?pCsc — SCITUATE GRANITE GNEISS
- pC(?)ms / pC(?)m — MARLBORO FM. incl SANDY POND MEMB
- pCv — VOLCANIC ROCKS, mostly mafic
- pCq — QUARTZITE
- pCa — ABSALONA GNEISS
- pCni — NIPMUCK GNEISS
- pCno — NORTHBRIDGE GNEISS
- pCb — BLACKSTONE GROUP
- pCg — GNEISS

Figure 3

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known only from clasts occurring in the Pennsylvanian Dighton Conglomerate (trip F-6) in Rhode Island. These fossils have long been recognized, but unfortunately for correlation, the localities at which they occur are structurally isolated by faults, plutons, or in the case of Hoppin Hill, by surrounding Pennsylvanian cover. The fossils have strong affinites with the Baltic Province, which many paleontologists consider geographically distinct from the North American province to which the Cambrian fossils on the western margin of the Appalachians belong. The rocks appear to comprise a thin, "platform"-type assemblage lapping onto the older Late Precambrian volcanic and intrusive terrane.

Siluro-Devonian Volcanic and Intrusive Complex:

Fossils have long been known from the Newbury Volcanics (trip A-16) north of Boston (Fig. 3). The fossils represent a brackish water assemblage that is hard to date exactly (hence the published dates have varied slightly), but Berry and Boucot (1970, p. 189-190) date the fossils as ranging from latest Silurian to earliest Devonian. It seems reasonable to correlate the volcanics north and south of the Boston Basin (Lynn, Mattapan, and Blue Hills Volcanics) with the Newbury. (The Mattapan has conventionally been dated as Carboniferous for reasons that no longer seem convincing; Naylor and Sayer, this volume, trips A-3 & B-3). As a group these volcanics appear to correlate with a major volcanic belt along the Maine and New Brunswick coasts, where the volcanics and related rocks have yielded fossils ranging in age from mid-Silurian to early Devonian. This would seem to be the most reasonable age range for the Massachusetts extension of the province. However, the next "logical jump" south to correlation with the volcanics of the fossiliferous Pennsylvanian Narragansett Basin emphasizes the need for caution with a possible Siluro-Devonian date for the Boston area volcanics. Certainly, the range in error for the radiometric dates does not rule out an earlier, possibly late Ordovician or early Silurian age favored by Cameron and others (1975) and Cameron and Jeanne (this volume) (trip A-5).

Related to these volcanics is a distinctive group of non-foliated, alkalic, one-feldspar granites north and south of the Boston Basin (Cape Ann, Peabody, and Quincy granites and probably the Sharon Syenite and related small bodies) (trips A-11, B-11). In the Blue Hills south of Boston, the Quincy Granite and its chilled marginal phase (the Blue Hills Porphyry, not shown separately on the map) intrude the volcanic rocks (Blue Hills Volcanics or Aporhyolite) and thus are slightly younger than the volcanics (trips A-3 & B-3). Isotopic ages on these granitic rocks range from 450 to 280 m. y. Naylor and Sayer (this volume) discuss why the ages in the Blue Hills area show such scatter and argue that the isotopic ages are consistent with a Siluro-Devonian age for both the volcanics and the granites. Elsewhere, the field relationships are not so clear-cut, with the result that two interpretations are possible: (a) the various isotopic ages are correct, indicating that the volcanic and igneous rocks were emplaced over a long interval of time, or (b) that the volcanic rocks are Siluro-Devonian as suggested by the fossils and the isotopic ages are scattered. The latter interpretation has been followed by Naylor in compiling the geologic map (Fig. 3).

The problem has been further complicated by recognition that large volumes of mafic intrusive rocks (mapped as Salem Gabbro) appear related to this same province (Bell and Dennen, 1972, and Dennen, 1972) (trips A-11 & B-11). In

interpreting the age relationships, however, the difficulty of distinguishing
Late Precambrian mafic rocks from those of the younger complex should be noted.

Boston Basin:

   The Boston Basin (Figs. 1, 3-4) is a topographic, structural (high-angle
thrust faults), and sedimentary basin whose source area was to the south. It
contains over 17,000 feet of argillaceous and conglomeratic sediments and vol-
canics (Billings, Fig. 4, this volume) (trips A-1 & B-1), whose age has been
debated for many years, with suggestions ranging from Ordovician to Permian
(A-2 & B-2, A-3 & B-3, and A-5). The Roxbury Conglomerate, a southern facies
of the lower half of the Boston Bay Group (Billings, Fig. 4, this volume),
contains three members of which the Squantum "Tilloid" is most famous because
of the debate over its glacial origin (trips F-1, A-1 & B-1, A-2 & B-2).
Further evidence for Paleozoic glacial activity in the Boston Basin is reported
from the lower Brookline Member (trip A-5).

   Conventionally, a Carboniferous age has been assigned to the Boston Basin
sequence. The rocks of this basin rest with mapped unconformity on the Dedham
Granodiorite which is now dated as Precambrian. The Mattapan Volcanics, possi-
bly Siluro-Devonian, are also older than the basin sequence as indicated by the
abundance of Mattapan clasts in the conglomerates of the Boston Basin sequence.
Plant fossils have been reported from the Boston Basin but they are not diag-
nostic for dating and considerable doubt exists that they are actually fossils
(Cameron, Jeanne and Schneider, 1975, and Cameron and Jeanne, this volume).
The lithology and stratigraphic sequence of the Boston Basin sediments and
volcanics do not correspond closely to those of the known Carboniferous Basins.
Naylor and Sayer (this volume) suggest a possible Upper Devonian age for the
Boston Basin rocks by correlation with the Perry Basin of easternmost Maine,
noting that the clast lithologies can best be explained if the Boston Basin
rocks were older than those of the Carboniferous basins to the south. Cameron
and Jeanne (this volume) and Cameron and others (1975) favor a Late Ordovician-
Early Silurian age for the Boston Basin by correlating the glacial event in the
Boston Basin to the regional glaciation of that age in northwest Africa. They
support this contention with the hypothesis that northwest Africa was possibly
once joined to North America via plate tectonics. For the age of the Boston
Basin to be older than Late Silurian would, however, require an older age for
the Mattapan Volcanics than that suggested by the regional correlations pre-
sented by Naylor and Sayer (this volume).

Pennsylvanian Basins:

   There are five Pennsylvanian or presumed Pennsylvanian basins in eastern
Massachusetts, assuming that the Boston Basin is older (Fig. 4). They are
characterized by generally low-grade metamorphism and by graywacke suites with
arkose, plutonic pebbles in the coarser sedimentary rocks, and few orthoquart-
zites (Quinn and Oliver, 1962). Volcanic rocks are virtually lacking except
locally in the Wamsutta Formation (red beds) of the Narragansett Basin. Poor
to well preserved plant fossils occur in some units.

   The Norfolk Basin, lying south of the Boston Basin, is connected to the Narr-
agansett Basin at its southwestern end (Fig. 4). These two basins have been
assumed to be of similar Pennsylvanian age on the basis of their physical con-
nection, similar lithologies and stratigraphy, and similar plant fossils. The
Norfolk Basin contains two formations, a lower Pondville Conglomerate (trips

Figure 4. Paleozoic sedimentary basins
of southeastern Massachusetts and Rhode
Island. All but the Boston Basin are
Pennsylvanian or presumedly Pennsylvanian
in age (from Lyons, Tiffney and Cameron,
1976, Fig. 1).

A-3 & B-3) and an upper Wamsutta Formation. Lyons, Tiffney and Cameron (1976)
described a new early Pennsylvanian plant fossil assemblage from the Pondville.

The Larger Narragansett Basin contains a rich Pennsylvanian flora, primarily
associated with coal seams in the Rhode Island Formation along its northern and
western margins (trip B-18). Some of the seams were mined during this and the
last century (Lyons and Chase, this volume). This basin contains a Pondville
Conglomerate – Wamsutta Formation sequence that is apparently younger than that
in the Norfolk Basin (Lyons and others, 1976). To the north, this sequence is
overlain by, as well as interfingered with, the Rhode Island Formation which
is in turn overlain by the Dighton Conglomerate. The Purgatory Conglomerate
to the south is equivalent to the Wamsutta (Mosher and Wood, Fig. 1, this vol-
ume). The degree of metamorphism in the basin increases from chlorite grade in
the north to garnet and staurolite grade in the south (Quinn, 1971) (trips F-6,
A-18, B-17).

The small Woonsocket and North Scituate basins are located about 10 km west
of the Narragansett Basin (Fig. 4). They contain the Bellingham Conglomerate,
which is believed to be time-equivalent with the Pondville Conglomerate of the
Narragansett Basin, but no fossil evidence has yet been found.

Pennsylvanian fossils also occur west of Boston at Worcester in what is now
interpreted to be a very small basin (trip A-12). It was dated as Early to
Medial Pennsylvanian using plant fossils (mostly poorly preserved) in phyllite
from the old Worcester coal mine (Grew and others, 1970). The better preserved
fossils indicate a Medial Pennsylvanian age correlative with the Rhode Island
Formation in the northern part of the Narragansett Basin (Lyons and others,
1976).

GEOLOGY OF THE CENTRAL HIGH-GRADE BELT

Between the Bloody Bluff Fault and the Clinton-Newbury Fault lies a belt of high-grade (sillimanite) metamorphic rocks (Figs. 1 & 3) (trips F-3, A-13, A-14 & B-14, A-15 & B-15). Rocks immediately west of the Bloody Bluff Fault are possibly related to those in the eastern, low-grade province, but apparently different sequences of rocks outcrop in the western part of the high-grade belt.

The major rock unit is the Nashoba Formation, a heterogeneous unit consisting mostly of felsic, biotite-gneiss, with lesser intercalated amphibolite, calc-silicate, and pelitic or quartzofeldspathic schists. Despite the heterogeneity of the unit, Bell and Alvord (1974) have shown that it can be subdivided into members showing considerable lateral extent (trips A-14 & B-14). East of the Nashoba these authors recognize a groups of dominantly felsic paragneisses, and to the west, a rusty-weathering schist designated the Tadmuck Brook Schist. Bell and Alvord (1974) interpreted all these rocks as a westward-dipping, west-ward-topping, homoclinal, geosynclinal sequence lying stratigraphically above the Late Precambrian province described above. Because the sequence is cut by numerous faults, some of which may be of very great magnitude, this interpreta-tion should probably be treated with caution. Along strike in eastern Maine are several major structural provinces, including rocks of the Ellsworth, Penob-scot, and Passagassawakeag "Groups." An alternate interpretation is that all, or some combination of this complex Maine terrane, may appear in Massachusetts as the Nashoba and related units. Ordovician fossils have been identified with-in this Maine sequence, but their structural position is uncertain and some of the rocks may be considerably older or younger than Ordovician. The rocks have been tentatively assigned to the Early Paleozoic in this compilation.

Rocks of this belt are cut by a heterogeneous group of granites and quartz diorites designated the Andover Granite. Zartman and Naylor (in preparation) report an Rb-Sr whole-rock isochron age of 415 ± 15 m. y. from aplites in the Andover Granite. This may be compared with an earlier Rb-Sr whole-rock age of 460 ± 23 m. y. (Hanford, 1965) based on samples including gneissic varieties of the Andover Granite.

GEOLOGY OF THE WESTERN LOW-GRADE BELT

Metamorphic grade drops abruptly across the Clinton-Newbury Fault, and for some distance to the west lies a belt characterized by low-grade regional meta-morphism (Figs. 1 & 3) (trips F-2, F-4, A-15 & B-15, B-13). The major strati-fied rocks of this belt are assigned to the Merrimack Group and are tentatively considered to be of Silurian and Devonian age. The basis for this assignment is correlation along strike with fossiliferous Silurian rocks in the Waterville area, Maine. Many of these rocks were formerly considered Carboniferous on the basis of fossils in a locality at Worcester, but it is currently believed that the Carboniferous rocks are restricted to a very small basin in the immediate vicinity of the fossil locality. In considering the correlation with the Water-ville sequence, however, it should be noted that several intervening plutons break the continuity of the beds along strike. The Merrimack Group is cut by the Ayer Granite, Dracut Diorite, and the Newburyport Complex.

The Harvard Conglomerate apparently rests unconformably on the Ayer Granite; its relationships to adjacent units are uncertain (trips F-4, A-15 & B-15).

METAMORPHISM

The patterns of metamorphism in eastern Massachusetts and vicinity are com-
plex. Several metamorphic events are probably involved but the timing and
extent of each is poorly understood.

The fact that Pennsylvanian rocks have been metamorphosed to high grade
(kyanite-staurolite) in southern Rhode Island must be strongly emphasized (trips
F-6, A-18, B-17). This metamorphism is related to the emplacement of the Narra-
gansett Pier and Westerly granites but appears to be regional in extent, with
garnet and chloritoid occurring in Pennsylvanian rocks as far north as northern
Rhode Island. This metamorphism dies out northwards. The rocks of the northern
part of the Narragansett Basin, the Norfolk Basin, and the Boston Basin are
strongly indurated but uncleaved, and diagnostic metamorphic minerals have not
been reported from these areas. The Pennsylvanian metamorphic belt continues
to the west. Clasts in the Bellingham Conglomerate (Woonsocket Basin) are
highly stretched and garnet occurs in the Pennsylvanian rocks at Worcester.
The knowledge that Pennsylvanian metamorphism is locally intense and somewhat
sporadically distributed has to be kept very much in mind when interpreting the
metamorphism of the older rocks.

In the western low-grade belt the metamorphism is probably Acadian but the
intensity is only biotite- to chlorite-grade, whereas Acadian metamorphism of
of sillimanite-grade is widespread a short distance further west.

In the eastern low-grade belt fossiliferous Cambrian and Siluro-Devonian
rocks show contact metamorphism near younger igneous bodies, but negligible
regional metamorphism. This observation indicates that Acadian metamorphic
effects have died out this far east. Most of the Precambrian rocks of this
belt show slight metamorphism (low greenschist facies) with higher grades of
contact metamorphism. This is consistent with the hypothesis that the Precam-
brian rocks were eroded to depths of several kilometers prior to deposition of
the Cambrian strata. It remains to be determined whether certain rocks show
higher grades of Precambrian metamorphism, and whether earlier episodes of
Precambrian metamorphism can be identified.

PLEISTOCENE GLACIAL GEOLOGY

Glacial ice flowed southward during the Wisconsin Stage, forming three lobes
in southeastern New England (the Buzzard Bay Lobe on the west, Cape Cod Bay
Lobe in the middle, and the South Channel Lobe to the east). The ice had two
major positions of standstill as evidenced by the two end moraines that occur
in southeastern Massachusetts, one of which forms Nantucket Island and Martha's
Vineyard while the other forms the Woods Hole area and the east-west part of
Cape Cod (Fig. 1) (trips A-10 & B-10). Other end moraines are located near
Plymouth (Ellisville Moraine) and the famous Beacon Hill in Boston is now also
considered to be an end moraine by Kaye (this volume) (trips A-6 & B-6).
Separate tills indicate several glacial ice advances and retreats in southeast-
ern Massachusetts (Leonard and others, this volume), such as in the Boston area
(trips A-6 & B-6). More than one till have been recognized elsewhere, such as
in the Worcester area where outwash, drumlins, and glacial lake features can be
studied (trips F-5 & B-5).

Ice contact features are in evidence in southeastern Massachusetts where pro-
glacial lakes existed in the relatively low and flat area of the Narragansett
Basin. Flowtill, derived entirely from superglacial debris, can be found in many
ice-contact features, such as kames, kame terraces, and ice-channel fillings
(Hartshorn, this volume) (trip A-7).

Glacially striated outcrops are common almost everywhere in New England
(trips A-6 & B-6) and drumlins abound in eastern Massachusetts, as can be seen
north of Boston (trips A-8 & B-8), in the metropolitan Boston area (trips A-6 &
B-6), and south of Boston (trips A-9 & B-9).

COASTAL GEOLOGY

The shoreline of southeastern Massachusetts is dominated by Cape Cod, Cape
Cod Bay, Martha's Vineyard and Nantucket Island which will be viewed from the
air on part of trips A-10 and B-10. Northward, the coast is dominated by Mass-
achusetts Bay with Boston Harbor centrally located. The northeastern region is
marked by Cape Ann with the Plum Island-Castle Neck barrier island system in
the Merrimack Embayment slightly to the northwest.

The coastal areas of eastern Massachusetts (trips A-8 & B-8, A-9 & B-9, A-10
& B-10) contain many glacial and non-glacial deposits or bare rock. Drumlins
are common at Plum Island (trips A-8 & B-8), Boston Harbor (trips A-6 & B-6),
and Nantasket Beach (trips A-9 & B-9). End moraines and outwash comprise most
of Cape Cod and the associated islands (trips A-10 & B-10). Bedrock dominates
some coastal regions, such as around Cape Ann (trips A-11 & B-11) and southward
(trip B-12) to the Boston Harbor and in the Nantasket (trips A-9 & B-9) and
Scituate areas south of the harbor. Salt marsh areas are ubiquitous along the
entire coast (trips A-8 & B-8, A-9 & B-9, A-10 & B-10). Dunes are well devel-
oped on barrier islands and Cape Cod (trips A-8 & B-8, A-10 & B-10). Sand
beaches are common up and down the coast. A "singing" sand pocket beach occurs
at Manchester north of Boston. A few cobble beaches occur at Gloucester, pocket
pebble beaches have developed around Cape Ann, and shingle beaches are present
at Nantasket (trips A-9 & B-9).

Glacial deposits consitute the main sediment source for the sandy beaches,
spits, bars, and barrier islands. The major storms that affect these coastal
features come from the northeast and longshore drift is generally southward on
north-south beaches.

ENVIRONMENTAL GEOLOGY

The relatively new concept of environmental geology is presented in several
field trips. Associated with urbanization are a host of new or aggravated
problems making demands on our natural environment and its resources. With
regard to the Boston area, the effects of urbanization on surface water quality
will be studied by trip B-19 on which the Charles River will be followed from
its relatively clean rural area through to the increasingly polluted urbanized
areas along its downstream course. The results of field testing during the
trip will be discussed. Downstream, the Charles River, originally an estuary,
is artificially impounded in the Charles River Basin between Boston and Cam-
bridge. A new Charles River Dam is currently being built at Warren Avenue in
Boston by the United States Army Corps of Engineers. It will provide flood

control by maintaining the basin at a constant elevation above sea level in order to prevent damages such as those caused by the record flood of August, 1955. This new dam is a multi-purpose project with provisions for flood control, recreational and commercial navigation, and future highway transportation. Trip A-19 will consist of an inspection of the second stage cofferdam excavation, exposing the foundation conditions.

North of Boston, two trips will visit areas that are now protected from man's abuse. Prior to the Middlesex Fells (trip B-7) becoming a reservation in 1896, it had a long history of abuse. Its vegetational mosaic is now different in character from that of the time of colonial settlements because of lumbering, livestock grazing and both natural and man-induced fires. The effects of man's attempt to prevent shoreline erosion on the northern end of Plum Island in northeastern Massachusetts will be compared to the relatively disturbed natural system in the Parker River National Wildlife Refuge area of the middle and southern parts of Plum Island (trips A-8 & B-8).

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BEDROCK GEOLOGY OF THE BOSTON BASIN

by

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Introduction

The Boston Basin of eastern Massachusetts is a lowland, at or close to sea level, bounded on the north by the Fells Upland and on the south by the Blue Hills and Sharon Upland (La Forge, 1932, p. 8). To the west the Basin merges imperceptibly with the Needham Upland, but to the east is flooded by the waters of Boston Harbor and Boston Bay. The term Boston Basin also refers to the structurally complex synclinorium occupied by the Boston Bay Group. This paper is concerned primarily with the bedrock geology of the Boston Basin and Blue Hills.

The interpretation of the major features of the geology given in the paper does not differ greatly from that given by Billings (1929) and La Forge (1932). However, there are a few major differences.

(1) In the earlier papers it was assumed that the Cambridge Formation overlay the Roxbury Formation. But Billings and Tierney (1964) have shown that the Roxbury Formation is a southerly facies of the lower part of the Cambridge Formation.

(2) The concept of large tear-faults (transverse strike-slip faults) is now abandoned.

The importance of the study of the geology exposed in 32 miles of tunnels in the Boston Basin has been emphasized elsewhere (Billings, 1976). In that most recent paper the Dorchester Tunnel was not discussed. The writer prepared the original report when the tunnel was being planned (Billings, 1964), including a detailed analysis of the core borings. During construction the geology was mapped by Steven M. Richardson, to whom I am indebted for some data given in this paper.

Lithology

General statement. Figure 1 is a sketch map to show the distribution of the formations. Because of scale, it is not

intended to show details.

Five major units are shown in Figure 1: (1) Precambrian,
(2) Cambrian, (3) Ordovician(?), (4) Mississippian(?), and
(5) Pennsylvanian and Pennsylvanian(?). The Triassic diabases
are not shown. The evidence for the dating will be discussed
under the various units.

Precambrian. The dating of many of the rocks as Precambrian is
based on exposures at Hoppin Hill, North Attleboro, 30 miles
southwest of Figure 1, where fossiliferous Lower Cambrian rests
unconformably on Dedham Granodiorite (Dowse, 1950). Thus the
Dedham and its comagmatic rocks are Precambrian, as well as
rocks into which they are intruded.

The Precambrian, which underlies large areas in Figure 1,
consists of metamorphic and plutonic rocks. The metamorphic
rocks are quartzite, amphibolite, and gneiss. The plutonic
rocks are gabbro, diorite, quartz diorite, granodiorite, and
granite. Detailed descriptions are given by La Forge (1932),
Chute (1966, 1969), and Nelson (1975).

Cambrian. The Cambrian rocks are confined to two areas. They
are extensively developed in the area extending from the Blue
Hills to Weymouth, a distance of nine miles. Their distribu-
tion is shown very diagrammatically in Figure 1. They are also
found at East Point in Nahant.

Traditionally the Cambrian rocks have been assigned to two
formations. The Weymouth Formation, consisting of red shales,
locally converted to hornfels, and a little limestone, is
Lower Cambrian. The Braintree Formation is a dark-gray massive
argillite of Middle Cambrian age. The very important paleonto-
logical studies by G. Stinson Lord and Benjamin Howell await
publication.

Ordovician(?). In Figure 1 the alkalic igneous rocks of the
Blue Hills complex have been assigned to three units: (1) vol-
canic complex, consisting of rhyolitic lavas and pyroclastic
rocks; (2) Blue Hills Granite Porphyry; and (3) Quincy Granite,
a riebeckite-aegirite granite. Zartman and Marvin (1971)
utilizing the Pb/U method, concluded this group is late
Ordovician.

Mattapan and Lynn Volcanic Complexes. The Mattapan Volcanic
Complex occupies three large areas in Figure 1, two to the
south of the center of the map, the other to the southwest.
Smaller areas are also present. The Mattapan is composed of
felsites and melaphyres (altered basalts and andesites), some
of which are amygdaloidal. A detailed description of this rock
in the Natick quadrangle (extreme western part of Figure 1) has
been given by Nelson (1975), who has identified crystal tuff,
lapilli tuff, breccia, and lahars. Much of the Mattapan un-

Fig. 1. Geological Sketch Map of Boston Basin and Blue Hills. See Fig. 2 for explanation of symbols for formations. In Fig. 1 Brookline and Dorchester Members are combined as Prbd. Tunnels labelled thus: mt, Malden Tunnel; cte, City Tunnel Extension; ct, City Tunnel; nmt, North Metropolitan Relief Tunnel; dbt, Dorchester Bay Tunnel; wrt, West Roxbury Tunnel; dt, Dorchester Tunnel.

Fig. 2. Explanation for Fig. 1.

Boston   Basin   Norfolk Basin

Mississippian ?   Pennsylvanian ?   Pennsylvanian

Boston Bay Group

Roxbury Conglomerate

Lynn Volcanic Complex	Mattapan Volcanic Complex	Brookline Member (with melaphyre lentil)	Dorchester Member (with melaphyre)	Squantum Member	Cambridge Argillite (with "Milton" quartzite) (Long dashes on map)	Pondville Conglomerate	Wamsutta Formation
Ml	Mm	Prb Prbm	Prd Prdm	Prs	Pc (Pcm)	Pp	Pw

Separately Distinguished only on sections;
Prbd on map

Blue Hills Block and Nahant

Precambrian   Cambrian   Ordovician ?

Lower   Middle

Basement Complex	Weymouth Formation	Braintree Argillite	Nahant Gabbro	Volcanic Complex	Blue Hills Granite Porphyry	Quincy Granite
P€	€w	€b	n	vc	bgp	q

doubtedly belongs to a depositional sheet laid unconformably above the Precambrian. But in places it is in dikes and small stocks cutting across the Precambrian rocks (W.O. Crosby, 1905; I.B. Crosby, 1928; Chute, 1966). The author has observed such relations in the West Roxbury tunnel. Such intrusive occurrences explain the sporadic character of small areas of Mattapan surrounded by older rocks.

The Lynn Volcanic Complex lies north of the Boston Basin and is generally correlated with the Mattapan Volcanic Complex.

The Mattapan and Lynn Volcanic Complexes are older than the Boston Bay Group, inasmuch as pebbles and cobbles of the volcanic rocks are common in the Roxbury Conglomerate. These complexes are classified in Figure 1 as Mississippian(?), as dated by Pollard (1965), but the paleontological evidence is not convincing.

Boston Bay Group. Traditionally the Boston Bay Group has been divided into two formations, the Cambridge Argillite above and the Roxbury Conglomerate below. There is a major facies change to the north, so that in Cambridge, Somerville, Medford, and Malden the lower part of the Cambridge Argillite is a northerly facies of the Roxbury Conglomerate. These relations are shown in Figure 4. The Boston Bay Group is over 17,000 feet thick.

The Brighton Melaphyre is not a stratigraphic unit. Melaphyres are both extrusive and intrusive, and appear sporadically throughout the Brookline and Dorchester Members.

The Roxbury Conglomerate has been divided into three members, from top to bottom, the Squantum, Dorchester, and Brookline Members (Emerson, 1917; La Forge, 1932).

The Brookline Member consists primarily of the typical "Roxbury puddingstone," with interbedded argillite, sandstone, and extrusive melaphyre. The maximum thickness of the Brookline Member is 4300 feet. But it thins rapidly toward the southern margin of the depositional basin; in Hyde Park it is 1000 feet thick, in Hingham it thins to 500 feet (Fig. 3).

The matrix of the conglomerate is a gray feldspathic sandstone. The pebbles and cobbles are well rounded, normally range in diameter from 0.5 to 6 inches, but locally may be as much as 12 inches in diameter. The clasts are chiefly quartzite, quartz monzonite, granite, and felsite, with small amounts of melaphyre and argillite.

The sandstones are fine- to medium-grained and some are so feldspathic that they may be called arkose. In some the beds, indicated by differences in grain size, range from 0.1 to 0.4 inch. Others that are 30 feet or more thick show no bedding. The colors are white, gray, pink, and red. Oscillation ripple

marks are found locally.

In the Boston area the term argillite has been applied to
rocks that some may prefer to call mudstone or siltstone. The
argillites are generally laminated (0.05 to 0.4 inch) but lack
the papery (0.01 to 0.05 inch) or platy (0.05 to 0.4) splitting
property characteristic of shales. The argillites in the Brook-
line Member tend to split into flags (0.4 to 2 inches thick) or
slabs (2 to 24 inches thick) parallel to the bedding. The
colors are pink, red, and green-gray; light-gray and dark-gray
shades typical of the Cambridge Argillite are rare. An excep-
tionally thick argillite extending east and west from the
Chestnut Hill Reservoir was erroneously mapped as Cambridge by
La Forge (1932).

Melaphyre is associated with the Brookline Member. Some
are intrusive, some are flows, and some are bedded tuffs and
breccias.

The rocks in the Dorchester Member are similar to those in
the Brookline Member, but the percentages are different. Where-
as the Brookline Member averages about 60% conglomerate, 20%
sandstone, and 20% argillite, the Dorchester Member averages
about 15% conglomerate, 25% sandstone, and 60% argillite. The
conglomerates are similar to those in the Brookline Member. The
sandstones are pink, red, and white; all are feldspathic. The
argillites are white, pink, red, and purplish-gray; some are
gray and greenish-gray similar to those in the Cambridge
Argillite. Locally the pelitic rocks are sufficiently fissile
to be called shales. Ripple marks are locally present.

The top of the Dorchester Member is defined rather readily
by the base of the overlying Squantum Member, which in most
places contains the distinctive tillite. In general the base
of the Dorchester Member is defined as the horizon above which
the conglomerate is less than 20% of the rock.

Melaphyre, both intrusive and extrusive, is locally abun-
dant in the Dorchester Member; notably in the area extending
from Brighton to Newton, and in Hingham.

In the central part of the Boston Basin the Dorchester
Member is about 1000 feet thick, but in Hingham it is only
about 600 feet thick.

The Squantum Member contains, in addition to conglomerate,
an unusual rock that many geologists consider to be tillite
(Sayles and La Forge, 1910; Sayles, 1914). There will be plen-
ty of opportunity to discuss at this meeting the origin of this
rock. Regardless of its origin, this rock is distinctive and
belongs to one stratigraphic unit. The sandy to argillaceous
matrix is dark-gray, purple, or green-gray. Generally the
matrix is massive, but elsewhere it is strongly cleaved. The
clasts are subrounded to angular, generally range from 2 inches

to 3 feet in diameter and some are even larger; at Squantum Southeast (Sayles, 1914) one clast is 8 feet long. The clasts are granite, quartz monzonite, quartzite, felsite, and melaphyre.

The Squantum Member ranges in thickness from 70 to 400 feet. In general, the distinctive tillite constitutes much of the member. However, where crossed by the City Tunnel Extension in Brighton, it is conglomerate and contains no tillite. The band shown in Hingham (Fig. 1) contains no tillite, but has an exceptionally coarse conglomerate.

The Cambridge Argillite is composed almost exclusively of gray argillite, in which the beds range in thickness from 0.05 to 3 inches. The shades of gray differ in intensity; the grains in the light-gray rocks are silt or fine sand, whereas in the darker beds they are clay or fine silt. Much of the argillite shows a rhythmic layering due to alternation of lighter and darker beds 0.3 to 3 inches thick. Graded bedding is rare. The ubiquitous preservation of this thin bedding indicates that burrowing animals were not present. Some beds of argillite seem to be as much as 3 feet thick, but close examination shows that they consist of laminae 0.05 to 0.1 inch thick. The argillites are slightly calcareous. The fractures parallel to the bedding are 5 to 50 inches apart; because of two or more sets of joints transverse to the bedding the rocks break up into parallelopipeda. Occasional beds of sandstone 0.25 to 0.5 inch thick show minute cross-bedding.

The most prominent quartzite in the area was called the "Milton Quartzite" by Billings (1929). But "Milton" was preoccupied (Wilmarth, 1936) and should not have been used. But rather than propose a new name at this time, it seems best to retain the old name in quotes. This hard white sericitic quartzite, 400 to 500 feet thick, can be traced for about two miles in Quincy (Fig. 1). It was considered to be Upper Cambrian because quartzite pebbles with Upper Cambrian fossils are found in Pennsylvanian conglomerates in the Narragansett Basin (La Forge, 1932, p. 19).

La Forge (1932, p. 101) also says that Upper Cambrian fossils were found in quartzite and shale just west of the Blue Hills, but there is considerable doubt that the supposed fossils are organic. Moreover, the band of "Milton Quartzite" shown on Figure 1 appears to be a member of the Cambridge Argillite (Billings, 1976). On the other hand, southwest of where the "Milton" is truncated by the Blue Hill Fault, a quartzite is intruded by granite (Chute, 1969). If this is Quincy granite, this quartzite is pre-Ordovician(?)(Zartman and Marvin, 1971).

In earlier papers (Billings, 1929, p. 106; La Forge, 1932, p. 43) a green, red, and yellow quartzite at Tufts College that is 40 feet thick was believed to overlie the Cambridge

and was called the Tufts Quartzite. Utilizing information from the City Tunnel Extension, it is now clear that this quartzite is a member of the Cambridge Argillite and is 7500 feet strati-graphically below the Squantum horizon.

Concerning the age of the Boston Bay Group, La Forge (1932, p. 41) says the following: "No fossils have been found in the Roxbury conglomerate except for a few short pieces of tree trunks that were collected near Forest Hills, probably in the Brookline conglomerate member. The pieces are casts of trunks from which the bark had fallen, and the genus to which they be-long is uncertain but is probably either Cordaites or Lepidodendron. Their age, therefore, can not be determined more closely than that they are either Devonian or Carboni-ferous." A re-examination of one of these specimens by Elso Barghoorn suggested it could be Calixylon or Cordaites, and the rocks could not be dated better than Upper Devonian through Permian (Tierney, Billings, and Cassidy, 1968). Re-gional relations indicate that the most likely age is Pennsylvanian or Permian.

A detailed discussion of the geology of the Norfolk Basin is beyond the scope of this paper, but is mentioned because it has a bearing on the interpretation of the geology of the Blue Hills. The Pondville Conglomerate of Figure 1 is composed of two contrasting lithologic types. The lower part, a few hun-dred feet thick, is commonly referred to as the "giant con-glomerate." Round boulders, 6 to 12 inches in diameter, are set in a matrix of feldspathic sandstone. The boulders are porphyritic alkaline granite, similar to, but not identical with some of the rocks in the Blue Hills. It may be incorrect to correlate this "giant conglomerate" with the type Pondville conglomerate. The upper part of the Pondville as shown in Figure 1 is a quartz conglomerate, the matrix of which is a light-yellow sericitic quartzite. The overlying Wamsutta For-mation is red slate, red sandstone, and gray conglomerate. Plant fossils show that it is Pennsylvanian.

Mafic Dikes. La Forge (1932, p. 45-50) gives the best dis-cussion of the mafic dikes. Most of them are diabase or al-tered diabase. Although many ages may be represented, some as old as Precambrian, others are younger than the late Paleozoic folding. These have traditionally been considered to be Triassic because of similarity to the Triassic diabases in the Connecticut Valley. The most famous in the Boston area is the Medford diabase dike, in places 500 feet thick.

Structural Geology

Introduction. The geological structure is shown by Figures 1, 3, and 4. The Boston Basin is bounded on the northwest by a thrust fault and on the south by a series of en echelon thrusts. The basin itself is characterized by folds plunging east-north-
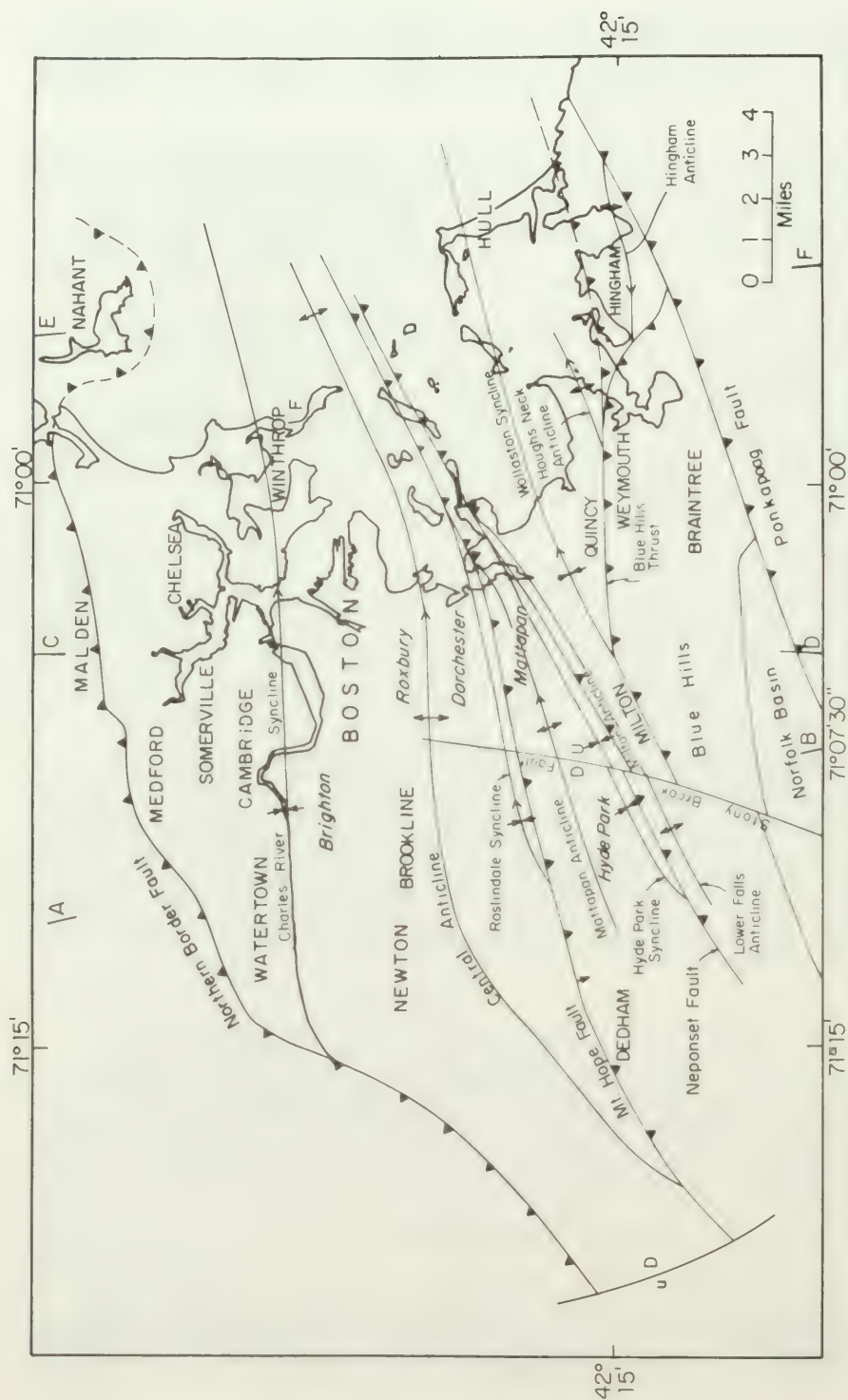
Fig. 3. Tectonic Map of Boston Basin and Blue Hills. Also shows cities and towns referred to in text, and location of structure sections.

east and several thrusts striking east-northeast.

Major Folds. The northern three quarters of the basin is domi-
nated by two major folds - the Charles River Syncline and the
Central (Shawmut) Anticline.

The morphology of the Charles River Syncline is well known,
partially from outcrops but also because it is crossed by two
tunnels - the City Tunnel Extension (Billings and Tierney, 1964)
and the North Metropolitan Relief Tunnel (Billings, 1975). The
distance between the two tunnels along the trace of the hinge of
the Charles River Syncline is 6.5 miles. The average plunge of
the hinge is 19° in a direction N 84° E. The dip of the north
limb in most places ranges from horizontal to 60° SE, but a few
anticlines and synclines with wave lengths of several hundred
feet are present (Fig. 4, section CD; Billings and Tierney, 1964).
In the north Metropolitan Relief Tunnel the northwest limb dips
30° to 60° SE. In the City Tunnel Extension the minor folds -
those with a wave length of one to three feet - have an average
plunge of 8° in a direction N 87° E. In the North Metropolitan
Relief Tunnel the few minor folds that were observed plunge
from 0° to 25° in a direction east-northeast (Billings, 1975,
p. 130).

The south limb of the Charles River Syncline was well ex-
posed in four tunnels - City Tunnel, City Tunnel Extension,
Main Drainage Tunnel, and North Metropolitan Relief Tunnel. In
most of these tunnels the dip is 15° to 30° N, but in the North
Metropolitan Tunnel it ranges from 0° to 80° N, but averaging
60° N.

The hinge of the Central Anticline trends between N 60° E
and N 80° E (Fig. 3). The map pattern (Fig. 1) and the atti-
tude of the bedding indicates that the fold is broad and open
and plunges 10° to 15° east. The north limb is the same as
the south limb of the Charles River Syncline. The south limb
dips 65° SSE. The axial surface dips about 75° N.

The Cambridge Argillite south of the Squantum Member on
the south limb of the Central Anticline is 4500 feet wide,
dips 75° SSE (Richardson, 1976), and tops to the south
(Billings, 1929). This is the north limb of the Roslindale
Syncline, which, however, has no south limb. Whether such
one-limbed structures should be called a syncline is a matter
of semantics. The Mt. Hope fault (Fig. 3) bounding this belt
on the south is discussed below.

South of the Roslindale Syncline a long tongue of Matta-
pan Volcanics (Fig. 1), with bands of Roxbury Conglomerate on
both sides, tapers to a point toward the northeast. This is
the core of the northeasterly plunging Mattapan Anticline
(Fig. 3). In the Dorchester Tunnel (Richardson, 1975) the
base of the Roxbury Conglomerate dips 60° NW on the northwest
limb. This contact, now considered to be an unconformity, was
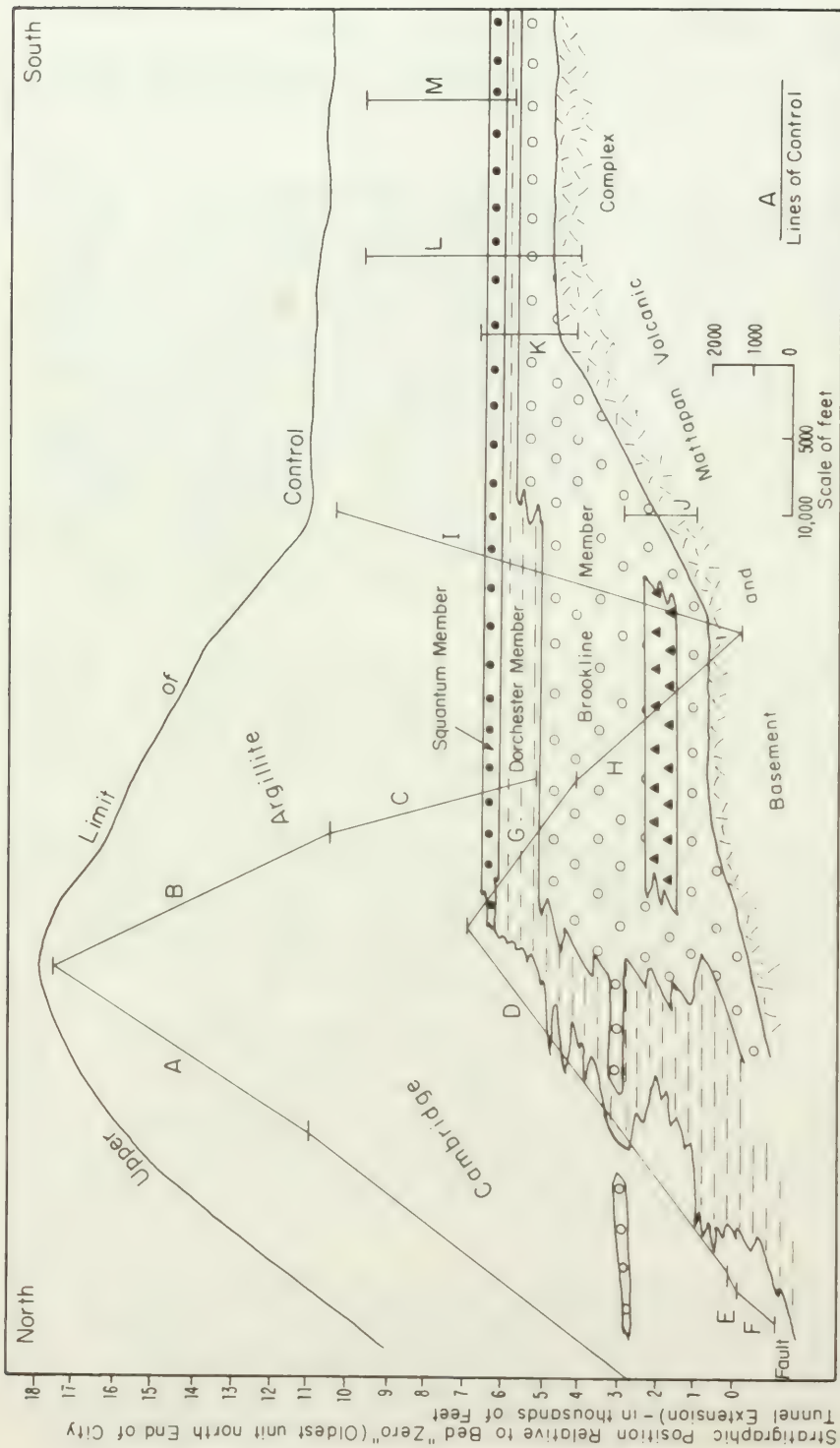
Fig. 4. Stratigraphy of the Boston Basin. Capital letters indicate nature of control. A. North part of North Metropolitan Relief Tunnel. B. South part of North Metropolitan Relief Tunnel. C. Main Drainage Tunnel. D. North part of City Tunnel Extension. E. Surface geology in Malden. F. Malden Tunnel. G. South part of City Tunnel Extension. H. Surface geology in Brookline. I. Surface geology Brookline to Dorchester. J. Surface geology north limb of Mattapan anticline. K. Surface geology south limb of Mattapan anticline in Hyde Park. L. Surface geology Dorchester Lower Mills. M. Furnace Brook at Adams Street, Quincy.

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formerly (Billings, 1929) believed to be a fault called the Sally Rock thrust. The base of the Roxbury is vertical on the southeast limb of the Mattapan Anticline. The Roxbury Conglomerate both northwest and southeast of the Mattapan Volcanics is in synclines; the former is given no name in Figure 3, the latter is called the Hyde Park Syncline.

In Hyde Park the Squantum Member forms the core of the Hyde Park Syncline (section AB, Fig. 4). At Squantum, the Squantum Member and the basal beds of the Cambridge Argillite are present. Along section CD the Squantum is absent, as will be discussed below in the discussion of the Neponset Fault. The Hyde Park Syncline is another syncline without a southeast limb.

The Lower Falls Anticline, named after the Lower Falls of the Neponset River, is shown on Figure 1 by a tongue of Mattapan Volcanics that tapers to a point toward the northeast. Moreover, at Lower Falls an argillite near the base of the Roxbury Conglomerate is exposed along the MBTA tracks in an anticline plunging 18° in a direction N 67° E (Billings, 1976).

The Cambridge Argillite is poorly exposed in the Wollaston Syncline. But the presence of the Roxbury Conglomerate both northwest and southeast of the Cambridge demonstrates the reality of the syncline.

The north limb of the Houghs Neck Anticline is well exposed in the vicinity of Furnace Brook in Quincy. Vertical beds of the Dorchester Member, Squantum Member, and Cambridge Argillite strike southwest into the contact with the Quincy Granite (Fig. 1). Further east conglomerates, intruded by melaphyre, are found in the core of the anticline. The south limb is hypothetical, based largely on the presence of Cambridge to the east.

The Hingham Anticline, which plunges steeply west, has a core of the Dedham Granodiorite; it is based on excellent exposures (W.O. Crosby, 1894).

Faults. In the City Tunnel (Tierney et al., 1968), City Tunnel Extension (Billings and Tierney, 1964), and Main Drainage Tunnel (Rahm, 1962), 318 minor faults were recorded (Billings, 1976). Of those 278 faults in which the displacement could be determined, 186 were normal, 51 were reverse, and 41 were vertical. The most prominent strikes average N 20° E, N 10° W, and N 50° W; dips are 80° to 90°, although some dips are as low as 50° (Billings, 1976). The average vertical separation of these faults was three feet. But in 39 of the faults, the nature and amount of the displacement appeared to be greater than the diameter of the tunnel and could not be measured.

Six major faults are shown in Figures 1 and 3.

The North Border Fault has been known for a long time and

Fig. 5. Structure Sections of Boston Basin. Location of cross-sections is on Figs. 1 & 3. See Fig. 2 for legend. Dip of all faults, except Stony Brook Fault, is based on observation. Sections arranged to give down-plunge view of structure; that is, section AB is structurally lowest, EF is structurally highest.

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has been considered to be a thrust (Billings, 1929, p. 107; La Forge, 1932, p. 63). The thrust was exposed in the Malden Tunnel (Billings and Rahm, 1966), where it is knife sharp, with no breccia or gouge, and dips 55° N. Lynn Volcanics are thrust over Cambridge Argillite that has been dragged into a vertical dip (Fig. 4, section CD). Further west various Precambrian units comprise the hanging wall. The stratigraphic throw is not necessarily great, but the length of the fault suggests it is large.

The northeasterly striking faults in the southern half of the Boston Basin are called thrusts despite the fact that they are now essentially vertical. It is significant that the synclines to the northwest lack southeastern limbs and the anticlines to the southeast lack northwestern limbs. The faults must have formed prior to any important folding (Billings, 1972, Fig. 10-1,A), dipped less than 45° SE, and then during the folding were rotated to their present vertical dip.

The Mt. Hope thrust trends east-northeast. Near the west end of the belt of Cambridge Argillite in the Roslindale Syncline (Fig. 1) the structural relations are clear near the Roxbury Latin School. Northwest of Center Street argillites of the Cambridge Formation, 2500 feet above the Squantum Member dip 60° S and ripple marks show they are right-side-up. Five hundred feet to the south the Precambrian Dedham Granodiorite crops out. A large fault, with a stratigraphic throw of at least 6000 feet is indicated.

Three and one-half miles to the east, near the line of the Dorchester Tunnel, both surface geology and observations in the tunnel indicate a large fault. In an abandoned quarry at the corner of Wildwood and Dumas Streets in Dorchester argillites of the Cambridge Formation, 4000 feet above the Squantum Member, dip 70° S; ripple marks show the beds are right-side-up (Billings, 1929, p. 117). A band of Roxbury Conglomerate lies a few hundred feet to the south. The actual contact, formerly exposed on Middleton Street, is a shear zone dipping 85° N (Billings, 1929, p. 117). The Dorchester Tunnel crossed this fault (Richardson, 1975). The Cambridge Argillite northwest of the fault, for a distance of 4300 feet dips rather uniformly 70° to 75° ESE. But for 200 feet northwest of the fault the beds dip 20° ESE. The fault plane strikes N 52° E and dips 85° NW. Southeast of the fault are felsites of the Mattapan Volcanics. The stratigraphic throw is 10,000 feet. Two and one-quarter miles to the northeast, northwest of Squantum, the Dorchester Member is apparently faulted against the Cambridge Formation under Dorchester Bay (Clarke, 1888; Billings, 1976).

The Neponset Fault is based in part on evidence in Hyde Park (Figs. 1 and 3). On the south limb of the Mattapan Anticline the Brookline, Dorchester, and Squantum Members appear in proper order dipping southeast. But directly south of the Squantum the Mattapan Volcanics crop out (Chute, 1966). The

stratigraphic throw is at least 2000 feet. Two miles to the
northeast minor thrusts accompany the fault (Billings, 1929,
p. 121).

Still further east, to the west and north of Lower Mills,
the folds plunge southwest, unlike most of those in the Boston
Basin. The end of the Squantum Member, as shown in Figure 1,
is due to this southwesterly plunge of a syncline. North of
Lower Mills surface data indicate a syncline plunging 15° SW.
The data in the Dorchester Tunnel are very clear on this point
(Richardson, 1975). A major syncline between the Mattapan
and Lower Mills Anticlines plunges 14° SW (Fig. 5, section CD).
The Neponset Fault has ended somewhere to the southwest. But
a similar fault is present in the Squantum area, where the
Squantum Member is thrust against basal Cambridge.

The Blue Hills thrust bounds the Quincy Granite on the
north (Figs. 1, 3, and 4). The evidence is clearest in Quincy,
where successive northeasterly striking units of the Boston Bay
Group - from east to west the Dorchester, Squantum, and Cambridge,
including the "Milton" - are truncated at the east-west contact
with the Quincy. Along Randolph Avenue near Milton Center this
contact is an east-west trench 50 feet wide and 20 feet deep.
Loughlin (1911) observed this fault during road construction and
states that it dips 80° S. This fault continues to the coast
at Nantasket (Hull). Here the best evidence is in Hingham
where, on the north limb of the Hingham Anticline, the basement
and all the members of the Roxbury Conglomerate are truncated
against the Cambridge Argillite in Boston Harbor.

In Weymouth a fault is shown in Figure 1 branching off from
the Blue Hill thrust, but exposures here are poor. Formerly
(Billings, 1929) this was considered to be a tear-fault.

The Ponkapoag Fault is of special interest as it slices
across the east end of the Norfolk Basin, the Blue Hills, and
the Hingham Anticline. It is over 18 miles long. In East
Weymouth, four miles east of where the Pondville Conglomerate
ends, the Ponkapoag fault is exposed in a railroad cut. It
dips 80° NW, with Precambrian Dedham Granodiorite to the south
and Middle Cambrian Braintree Formation to the north. Down-
throw is to the north, but sufficient data are not available to
calculate the stratigraphic throw here. In Hingham (Billings
et al., 1938, p. 1882) the Dedham south of the fault is in con-
tact with basal Cambridge. The stratigraphic throw is at least
1340 feet.

By analogy with the faults to the north, it is assumed
that the Ponkapoag fault originally dipped south and has been
rotated into its present position. It is possible that this
fault formed with its present attitude as an upthrust.

One and four-tenths miles N 60° E of Watertown Square,
east of School Street, a coarse conglomerate was formerly ex-

posed in an abandoned quarry. Sayles (Billings, 1929) con-
sidered this to be the Squantum Member. Be that as it may,
Sayles, Billings, and La Forge (1932) agreed that it was at
the top of the Roxbury Conglomerate. La Forge believed it
was in the core of an anticline, whereas Billings (1929, 1976)
assumed it was bounded on the north by a thrust.

But the structure observed in the City Tunnel Extension
(Billings and Tierney, 1964) indicates that this is a tongue
of conglomerate, 4500 feet below the Squantum, extending north-
west into the Cambridge Argillite (Fig. 4).

The Stony Brook fault is a large cross-fault striking N
10° E. Billings (1929) formerly considered this to be a strike-
slip fault. It is now considered to be a vertical fault, with
the west side down-thrown 2100 feet. This deduction is based
largely on relations in the Roslindale Syncline. The Squantum
Member, striking east-west, dips 55° S and is offset 1470 feet.
The east-west vertical Mt. Hope Fault is offset little or not
at all. A graphic solution gives the net slip (Billings, 1972,
p. 559-563).

The Dorchester Tunnel crosses the Stony Brook Fault zone
(Fig. 1). The southeast end of the zone is 160 feet southeast
of the main line of the Penn. R.R. The northwest end is 4700
feet to the northwest. Inasmuch as the tunnel is diagonal to
the N 10° E strike of the fault, the width of the zone is about
3500 feet. Forty-nine percent of the zone is so fractured that
steel support was necessary (Richardson, 1975). The rocks were
highly altered and flows of groundwater were common.

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OUTLINE OF THE PLEISTOCENE GEOLOGY

OF THE BOSTON BASIN

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Introduction

The Boston Basin is both a structural and topographic feature.
Structurally, it consists of relatively unmetamorphosed folded and faulted
sedimentary and volcanic rocks of Late(?) Paleozoic age, surrounded on the
north, south, and west by older granites and other crystalline rocks.
Eastward, the basin extends out to sea where its composition and limits have
yet to be determined. It is a topographic basin largely by virtue of glacial
erosion which preferrentially excavated the soft fine-grained basin rocks,
such as argillite and tuff. Outcrops of the harder basin conglomerates and
volcanic flowrocks, however, are at altitudes comparable to those of the
surrounding rim area. On the north, the rock floor of the topographic basin
lies about 50 m on the average below the surrounding uplands; on the south,
it is generally less than 15 m; and on the west, the difference in elevation
is barely noticeable.

There is a sharp break in the Pleistocene terrain at the margin of the
topographic basin in the Boston area. Except for a few drumlins (Fig. 1), the
drift on the uplands is thin and patchy and knobby rock outcrops abound. In
the basin there is a subdued glacial outwash topography broken by many drumlins.
Rock outcrops are rare. The surface of the plain drops below sea level to
form Boston harbor with the drumlins making up most of the islands in that
body of water.

Beneath the simple surface of this lowland plain there are traces of
a complex geological story in the clays, sand, gravels, and sheets of till.
The thousands of foundation borings made in the area and the numerous deep
excavations for the foundations of large buildings have yielded evidence of
a succession of glacial advances and retreats. At least two of these were
in the late Wisconsin, but there are bits and pieces of evidence left by
earlier glaciations that undoubtedly range back to at least Illinoian time.

The Pleistocene section is suprisingly poor in till and rich in
outwash, including thick rockflour clays. There appears to be no widespread
till blanket left by the full-bodied Wisconsin ice that built the large
terminal moraines to the south at Cape Cod and the islands. For this reason
it is difficult to place the drift-stratigraphy into the framework of these
major glacial events. The geomorphology of the basin drift is only of minor

value in working out the glacial story, in part due to man's success in changing the landscape by filling and grading but also due to the fact that the older surface forms have been modified, destroyed or buried by younger events and deposits.

In Boston, as anywhere else in New England, the Pleistocene geologist must think glaciologically and in four dimensions. When all the data are carefully considered, one is slowly led to conclude that some of our long-held assumptions about Pleistocene glaciology need revision. Among the concepts that first have to be formulated and then accepted with a clear conscience in order to build a coherent framework for the glacial story are: 1) glacial erosion was very variable in its effectiveness and a given glaciation did not entirely remove the deposits of earlier ice sheets; 2) the deposits of a major glacial event are not ubiquitous but rather, patchy; 3) ice sheets need not have deformed or compacted (consolidated) overridden deposits; 4) under certain conditions, sheets of preëxisting sediments were dislocated from the glacial bed and transported englacially without undergoing drastic, or even noticeable disturbance or disaggregation. As a consequence of these conditions, the recognition of the age of any drift becomes uncertain, particularly if the weathering profile has been removed by the erosion of a subsequent glaciation. Moreover, the surface drift cannot be assumed to date from the last glaciation. A study of rock lithologies of clasts in till may be helpful in separating drifts but only if flow directions of the responsible ice sheets were markedly different. Even here, however, there are difficulties because successive ice sheets reworked pebbles from older drifts, creating thereby an ever-widening fan of distribution with which to confound the geologist.

Glacial transportation of intact plates of older sediment is particularly bothersome because these may have survived glaciation in such a natural manner that one readily misreads them as being in their place of origin. A pile-up of several plates of sediment, as in the Beacon Hill moraine (Kaye, in pressB) or in the Gay Head moraine of Martha's Vineyard (Kaye, 1964a), can easily result in a stratigraphic misinterpretation where relative ages of sediments are assigned on the basis of superposition when, in fact, they may be like a well-shuffled deck of cards, where the oldest need not be on the bottom.

If the glacial geology of the Boston basin is different, or more complex, than geology seems to be in many places in the interior of New England, perhaps this can be attributed to Boston's location: first, at the margin of the marine environment and secondly, at the margin of two major ice currents, or lobes. As we shall see, the direction of ice flow at Boston varied from southwest to east, through an arc of about 135° in azimuth. Represented here are diversional interlobate currents and ice currents that were antecedent to the major Wisconsin glaciation, as well as the normal lobate currents belonging to that event.

Feeble ice flow (in comparision to that prevailing to the east and west) characterized the Boston area during much of Wisconsin time. This situation is normal to an interlobate position, for a lobe, after all, is only an expression of varying rates of glacial flow, the greatest at the center of the ice current (the lobal axis) and the least at the margins. At one time, there even appears to have been virtual ice stagnation at Boston

while to the east and west ice was flowing vigorously.

Boston is at the marine shore today; and it appears to have been at, or close to, the marine limits during much of Wisconsin time. The effects of the sea on the ice sheet were many. For one, it provided bouyancy thereby relieving the bed of the ice from full bottom pressure. At times, when the ice was thin enough and the water deep enough, the ice may even have floated (shelf ice). However, the factors to be considered in determining the amount of marine bouyancy on ice at Boston are difficult to assess knowing as little as we do. The equation must include expressions for crustal (isostatic) levels, eustatic sea levels, and ice thickness.

Glacial Flow Directions

Four types of indices of glacial flow have been used: striations and grooves on bedrock, elongation of drumlin axes, lithologies of clasts in till and their probable source outcrops, deformational structures in overridden deposits. Many hundreds of striation and groove localities have been measured. It was found that all freshly exposed bedrock surfaces are well-polished, striated, or grooved and striated. Large grooves (as distinct from striations) all trend east to east southeast ($S60^{\circ}E$). Striations, on the other hand, range through about 135° azimuth from east through south to southwest. However, these can be broken down into 4 separate striation groups representing separate glaciologic events: (1) highly variable east to southeast flow, (2) south southeast flow that varied back and forth within the range $S32^{\circ}E$-$S16^{\circ}E$, (3) southerly flow, and (4) southwest flow.

The elongation directions of drumlins exhibit this same broad range of orientations. However, besides the classically streamlined drumlins, there are drumlins that are rounded in plan, compound drumlins, curved and sigmoidal drumlins. Some of these represent modification of initial streamlined drumlins by later ice currents. In a few places, bedrock striations have been exposed beneath drumlins and these seem to diverge somewhat from the direction of elongation of the overlying drumlins.

In an area where much of the bedrock is covered with drift and our knowledge of the distribution of rock types is therefore limited, the use of pebble lithologies in till for establishing glacial flow patterns is difficult. Nevertheless, there are certain key rock types that as far as we know have only one outcrop, or outcrop area (viz. Quincy riebeckite granite, Blue Hills quartz porphyry, Roxbury conglomerate, Nahant gabbro, serpentinite of Lynnfield, just to list a few) and which are easily recognized in the field. Unfortunately, however, little is known about the submarine rocks offshore to the northeast and east, or even within Boston harbor. It has been found that rock suites rather than key index rocks provide a sounder way to derive the direction of glacial transport. This involves taking all of the dominant rock types and matching them with the bedrock map of the area in order to establish a "best fit" between clasts and map. Refining one's eyes to recognize rapidly the many rocks of the area and their variations is essential to the process. Fortunately, clast sampling is greatly facilitated in Boston harbor because the many drumlin islands are rimmed by beaches that consist almost entirely of pebbles and boulders from adjacent till cliffs. One has only to slowly walk these beaches to scan many thousands of pebbles

in a short time. These pebbles, however, are a mixture of all horizons exposed in the cliffs. It is quite probable for example, that some of the drumlins include a complex of deposits contributed by shifting ice currents or by several distinct glacial events. Pebbles from all zones are mixed together on the beach. Two drift components of this kind have been recognized by comparing beach pebbles in front of low cliffs with those fronting high cliffs; the former giving only the last drift components, the latter both.

Complex deformational structures in the drift have been exposed in many foundation excavations in and about the city. Most of these are tied into two late glacial events, the Beacon Hill readvance and the Back Bay readvance, described in more detail below.

When all of these types of data are assembled, both from Boston and from adjacent areas, the picture of ice flow that emerges is shown in Table I. The very strong easterly flow indicated by deep, wide grooves is a particularly provoking episode. It can only be explained by the absence of a glacial lobe to the east. If this were so, then mainland ice simply followed the topographic gradient, which in the coastal zone of eastern Massachusetts is offshore to the deeper basins that lie to the east under Massachusetts Bay. Perhaps the development of the Laurentide ice cap proceeded from west to east and mainland New England was glaciated before Maine, the Maritimes and the adjacent continental shelf. Later, when the offshore lobes nad developed, glacial flow at Boston was confined to a rectilinear flow path towards the moraines of the southern shore. Here, however, we are confining our conjectures to the Wisconsin stage. Perhaps, the strong easterly flow was older; there is some evidence for this.

With glacial waning, divergent flow patterns redeveloped. The southwesterly flow is especially interesting and chronologically puzzling. To the south of Boston, in the Plymouth embayment, it probably was late Wisconsin for there is reason to think that an active ice lobe occupied Massachusetts and Cape Cod Bays after onshore ice to the west had stagnated and thinned. In Boston, the evidence for a late southwesterly flow into Boston harbor is less clear. To the north, in the lower Merrimack valley, where this flow is indicated by an alignment of drumlins that extends many kilometers to the southwest, there is some indication that it was fairly early in the Wisconsin. In any event, it is reasonable that ice flowed from the offshore lobe to onshore positions if the balance of ice in the two areas was such as to make this possible. The history of glacial fluctuations in its 4-dimensional entirety in eastern New England during the whole of the Wisconsin stage is a subject worthy of much more investigation than it has ever received. There certainly was time enough to allow substantial ice withdrawals and readvances, of changes in ice balance between lobes; and from the glimmer of insight that Boston provides, it appears almost certain that the 80,000 or so years of Wisconsin time did not pass simply with a stable ice sheet banked up first behind the outer and then the inner moraines and with a brief parting episode of minor pulsations of the ice front and the scattering of outwash over the landscape.

Table I

Glacial flow directions at Boston;

in approximate order of occurrence,

oldest on bottom

F. Lobate spreading to south and east (Back Bay readvance)

E. South (Beacon Hill readvance)

D. (?)Southwest

C. South-southeasterly (variable, mostly 32°, 22°, 16°)

B. Easterly to southeast (very variable, $80^{\circ}-38^{\circ}$)

A. Easterly; wide, deep grooves

Drumlins

An examination of the topographic maps (Lynn, Hull, Nantasket, Boston,North, Boston South, Lexington, and Newton $7\frac{1}{2}$' U.S. Geol. Survey topographic quadrangles) will show that the drumlins in the area come in many shapes and sizes. Although drumlins with the classical streamlined form are numerous enough in Boston harbor and west and south of Boston, the shapes vary so greatly that one hesitates to designate some of the hills as drumlins.

Submarine seismic profiling in the harbor and in Massachusetts Bay to the east shows many drumlins that are entirely submerged and more or less buried in later marine clays. Small drumlins, therefore, may represent only the tops of larger features that are partially submerged or buried.

The relationship between elevation of drumlins and the underlying surface of bedrock must be kept in mind. Obviously, the tops of drumlins reach higher elevation where the underlying bedrock is high than where the bedrock surface is low. This relationship seems to have a bearing on the distribution of drumlin islands and particularly on the several east northeast-bearing chains of drumlin islands in Boston harbor — for example, Peddocks Island and Long Island - which follow the strike of the bedrock and surmount ridges on the bedrock surface.

Many harbor drumlins are cliffed (Kaye, 1967) and these provide the best places to study the composition and structure of the drumlin interior. Several deep excavations in the Boston area exposed largely eroded remnants of drumlins whose existence was not suspected because they had no topographic expression. An example is the small drumlin, most of which lies buried beneath the Beacon Hill moraine and which was exposed during the building of One Beacon Street. Another is a much eroded drumlin in Cambridge, part of which underlies Harvard Yard. This was exposed in the excavations for the Pusey Library and the Cambridge St. underpass, adjacent to the Yard.

Most drumlins consist of compact, very well-graded medium greenish-gray till with a cohesive sandy clayey silt matrix. Boulders are sparse and cobbles and pebbles are predominantly of very local rock types. The top 6-15 meters of drumlins are oxidized to a characteristic light buff color; beneath this the unoxidized till is greenish to bluish gray. Layering, or stratification, has been found in all freshly-exposed drumlins. This consists of thin sandy, silty, and even gravelly layers, interbedded with till. The layers of sorted sediment range from a few centimeters to a meter or more in thickness. The spacing of these layers varies within the till. Some exposures of drumlin till show only a few of these beds of sorted sediment; others show many. In most the layers of sorted sediment are discontinuous. Gravel layers seem to grade into typical till. The thin silt interbeds not uncommonly show signs of intense shearing action. Indeed, it is not clear whether some of the fine-grained interbeds are sedimentary in origin or are of a cataclastic origin, a type of gouge that was produced during the formation of the drumlin. In fact, the entire problem of drumlin origin has been investigated but no single origin seems capable of explaining them all.
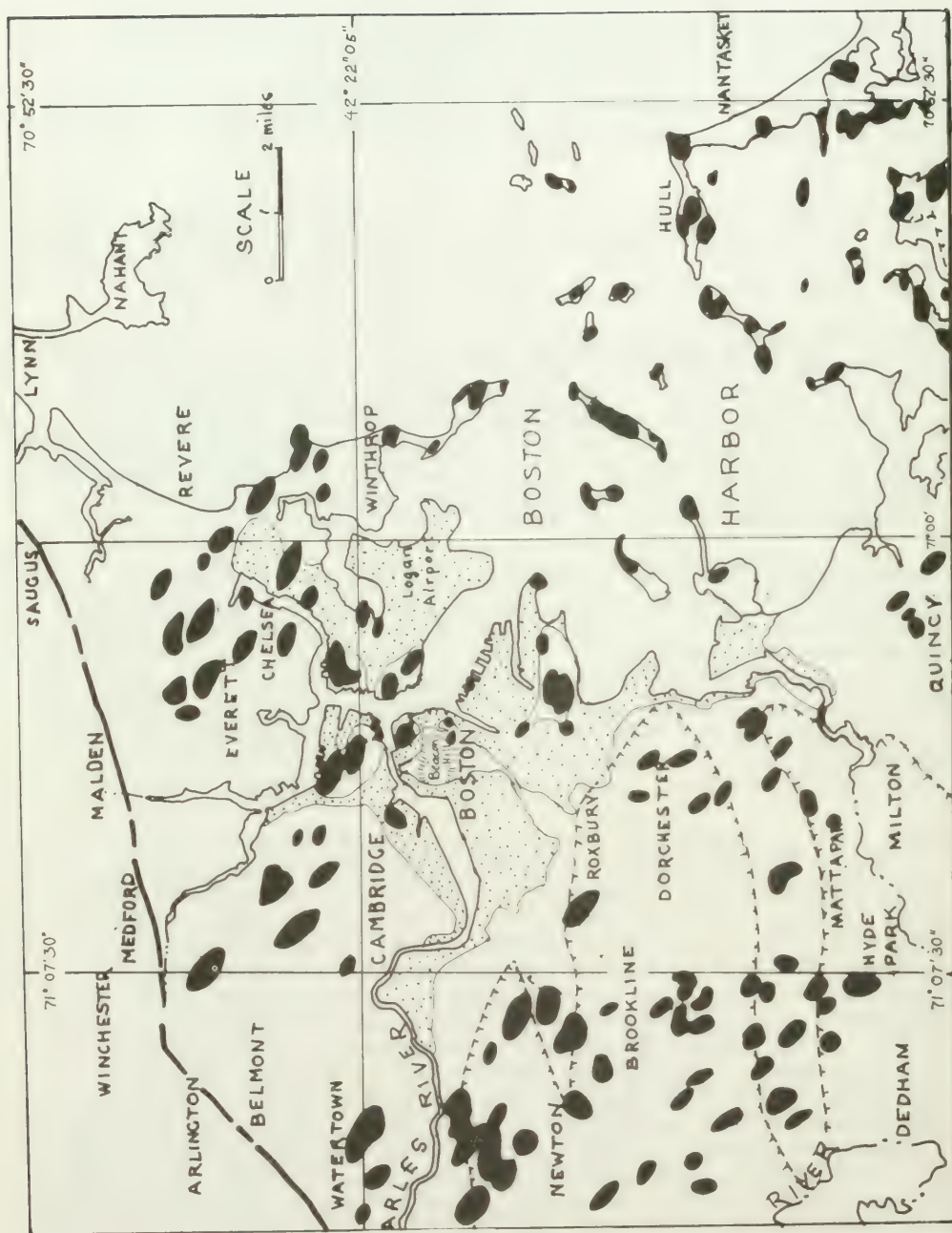
Figure 1 – Part of Boston basin showing: 1) drumlins (black); 2) boundary fault on north side of basin (heavy broken line); 3) major outcrops of conglomerate and volcanics within basin (fine dashed line, ticks towards these rocks); and 4) major areas of made-land (stippled).

One type of drumlin clearly seems different from others. These are till hills that grade laterally into stratified clay and that generally lack the simple elongate drumlin shape. Rather than the flanking clay being younger than the drumlin, both clay and drumlin seem to have been laid down at the same time. Perhaps these drumlins are simply lenticular masses of till left by large dirty icebergs stranded in the clayey bottom.

Sea cliffs show that many drumlins have an overall anticlinal structure, with the strike and dip of the layers more or less conforming to the surface of the drumlin. Some have this structure truncated thereby showing the effect of later glacial erosion. Some exhibit unconformities. The anticlinal structure may be constructional, that is, the ice having deposited till layer by till layer over an initial nuclear concentration. Or it may be the result of true arching of the ice under glacial pressures which centripetally deformed underlying or bed sediment. There are indications in the sheared silt zones that this might have occured.

Some drumlins are known to overlie bedrock directly but from borings we know that others overlie sands, gravels, or clays that appear to be earlier than the drumlins rather than interdrumlin beds. True bedrock-cored drumlins are not known here. The distribution of drumlins appears to be random relative to details of bedrock topography. The association of a few drumlins with bedrock knobs, such as the Parker Hill drumlin, is thought to be coincidental.

Interglacial Fossil Marine Shells

Fossil marine shells are found in the till in many harbor and near-harbor drumlins and in some of the outwash gravel in the same area. These fossils provoked much interest in the last century, and the last and as yet most comprehensive discussion of them was by Crosby and Ballard (1894). The total fauna listed by those authors consisted of 52 species of mollusks, 2 species of barnacles, and 1 crab. I have been able to find only a small percentage of these. The most abundant fossil by far is Mercenaria mercenaria (quahog, cherrystone, chowder clam, etc.), which always occurs as broken fragments, and to a lesser extent Venericardia borealis. Shells of the former species are unusually thick when compared to shells of the same species living in New England waters today.

Shells are found only in the gray unoxidized till, and it is quite certain that their absence from the overlying oxidized till is simply the result of weathering and leaching. The best collecting therefore is in high sea cliffs in harbor drumlins where there is ample exposure of unoxidized till. Shells were also reported by well diggers in the last century from drumlins that are located several kilometers from the harbor. It is apparent that we cannot claim to know the full distribution of fossiliferous drumlins for the simple reason that the deep interiors of most drumlins have not been exposed as have the cliffed drumlins in the harbor, or if they have been exposed, no geologist came by to notice the shells and to report them.

Suprisingly, the delicately sculptured surfaces of the shells are intact. Why the shell surfaces were not abraded when all the rock and mineral fragments that make up the till are scratched, faceted and fractured

is puzzling. One wonders why the shells were spared the rough glacial
milling that is evident in all the other components of the till. Perhaps the
answer is that many were not spared, and we see only the exceptional few
that were. Or perhaps the shells were introduced into the till mix in a
different manner from the rock components. This is an intriguing
conjecture but so far no suitable mechanism has come to mind.

The fauna (see Crosby and Ballard, 1894) includes temperate to cold
water and shallow to deep-water species. Mercenaria mercenaria today occurs
only sporadically north of Cape Cod and, as mentioned earlier, the thick
shell development is more characteristic of southern coastal waters than of
New England. Some of the distinctly cold-water species in the till are also
found in the late Wisconsin marine clays in the Boston area and are
characteristic of circumpolar seas.

What is the explanation for the faunal mixing? When and where did the
organisms originate? Do they represent one or several distinct stratigraphic
horizons within the drumlins? Unfortunately, none of these questions can be
answered with surety. Radiocarbon dating of Mercenaria mercenaria fragments
gives ages greater than $37,000$ C^{14}yrs. B.P. (H-1125). Probably the temperate
water species are interglacial, most probably Sangamon. There is even the
possibility that they are late Tertiary, as mentioned by Crosby and Ballard
(1894). These same authors also suggested that the cold-water elements
represent climatic deterioration at the onset of the Wisconsin prior to the
arrival of the ice sheet at Boston. There is, however, a possibility that the
colder species are derived from an interstadial marine clay within the
Wisconsin. We know that these exist and that the drumlins are complexed
of pre-existing deposits as well as rock debris freshly plucked, rubbed,
and scraped from rock ledges. If we knew just where within the drumlin the
different species came from we might discover that the cold and warm species
are not physically mixed but are separated into distinct zones, or strata
(the stratified structure of the drumlins has been mentioned). Unfortunately,
these data are lacking, principally because most shells are picked up on the
talus at the foot of the slope rather than plucked from undisturbed till
in the steep face of the cliff; they therefore may have come out of any of
the strata exposed in the cliff.

The question of where the shells originated must be considered
because of its bearing on glacial-flow directions. The distribution of
fossiliferous drumlins, particularly when considered within the framework
of the orientation of drumlin axes and the probable direction of dislocation
of rock clasts in the till, initially suggests that the interglacial
shoreline followed fairly closely the margins of the Boston topographic
basin and, indeed, appears not to have deviated substantially from the
present shoreline and therefore from present relative sea level. When we
consider, however, the deep water species, this seems less probable for
there was neither sufficient room nor the necessary depth of water within
this narrow coastal strip north and west of the drumlins to provide the
proper habitat.

Two possible explanations for the mixed fauna come to mind. One is
that the deep water species were transported from deeper waters to the east
to their present nearshore position. Even though there is evidence of such

glacial flow (Table 1), the clasts of the till in which the shells are
embedded and the drumlin axes strongly indicate east to southeast flow. The
second, and more probable, explanation is that Sangamon sea level was
higher, relative to today's sea level, by at least 30 m. This would allow
a narrow zone of deep water from which the deep water species might have
come to the north and west of the fossiliferous drumlins.

Pre-Wisconsin Deposits

Very much decomposed gravel is a conspicuous component of the Beacon
Hill moraine (below). This deposit is dark brown in color and contains many
soft, thoroughly decomposed, and manganese-stained argillite, diabase, and
granitic pebbles. In places, the gravel is "openwork" (lacking in matrix)
and in others the pebbles are embedded in a matrix of white silty clay. As
explained below, the gravel appears to have been glacially dislocated
and piled up along with less altered sediment into the moraine. The
dislocation mechanism is thought to involve the freezing of the glacial sole
to the bed-sediments which then become part of the glacial mass, moving when
flow energy attains sufficiently high levels. The position of these gravels
in the morainic pile-up is generally near, or at the top. This suggests that
the true stratigraphic position of these gravels was the reverse, that is,
at the bottom, for the ice appears to have dislocated underlying sediment
plate-by-plate, mining progressively downward. The oldest deposit is the
last to be dislocated and the last to be transported into the moraine.

The Harvard Yard drumlin may be pre-Wisconsin. As seen in the
excavation for the Pusey Library, this drumlin was weathered to a depth of
at least 12 meters prior to having been more or less planed down by later ice.
All of the deposits in the Harvard area sequence overlie this erosional
platform. As with the old gravels just described, it would appear that at
least an interglacial interval was required to produce the old weathering
profile that is now very much truncated.

The gravel and clay beneath drumlin till which have been found in
borings may be pre-Wisconsin in age. At present there is no way of dating
these deposits, or for that matter, the sorted sediment found interlayered
with drumlin till. In fact, there is no way of dating any of the drift except
only the most recent. To assign a Wisconsin age to part or all of these
deposits is more an act of faith than of science.

Beacon Hill Moraine [1/]

Beacon Hill gives us the first complex of deposits to yield a good sequential story. The hill has long been classified as a drumlin (viz. LaForge, 1932) for it has about the right shape and elongation, and it consists of drift which was presumed to be till. There is a fundamental error here, however. The shape before the 19th century was not that of a drumlin and the contents of the hill have been assumed.

Prior to 1800, when real estate developers began to grade Beacon Hill (Whitehill, 1968), the crestline was highly irregular, in profile and in plan. In profile there were three fairly isolated sharp peaks, in the east, central, and western positions (Fig. 2). In colonial times, these earned for the hill the name Trimountain, or its variants, Tramount, and Tremount. The name Beacon Hill came into usage for the entire feature only in the 19th century; before that it had sometimes denoted only the central and highest of the three peaks on which an alarm sentry, or beacon, had been built.

None of the maps of Beacon Hill that date from the time of the original three peaks give a very clear picture of the topography of the hill. The accompanying map (Fig. 2) was therefore reconstructed from available contemporary cartographic and verbal descriptions. From these we see that the original hill was somewhat arcuate in plan, concave to the north. This fact is of importance in establishing the origin of the hill because the major structural lines in the hill appear to conform to this shape.

[1/] It is perhaps unfortunate that the only way to decipher the Pleistocene geology of Boston is to follow deep foundation excavations. Certainly, this is the only way to get at the stratigraphy and the structural relationships that lie beneath the surface and which contain the major clues to the story we seek. I say "unfortunate" because doing geology in this way -- a sort of looking into tiny windows opened here and there at random -- is like putting together a large and complex jigsaw puzzle in which the individual pieces by themselves throw little light on the nature of the full picture or, else, allow for a multitude of interpretations. And like a jigsaw puzzle, where the entire picture in all of its detail may allude us until almost the very end, so the geologic interpretation of the Beacon Hill morainic complex seemed forever in a state of flux. Each new excavation brought new insights and new interpretations. Each endeavor to set down the story in print later turned out to be only a description of the "state of the art." All of this is by way of an explanation, if not apology, for some of the conclusions reached in a paper on the Beacon Hill moraine that was written over two years ago and which only now is about to appear (Kaye, in press B) and which is partly at variance with what is described here.

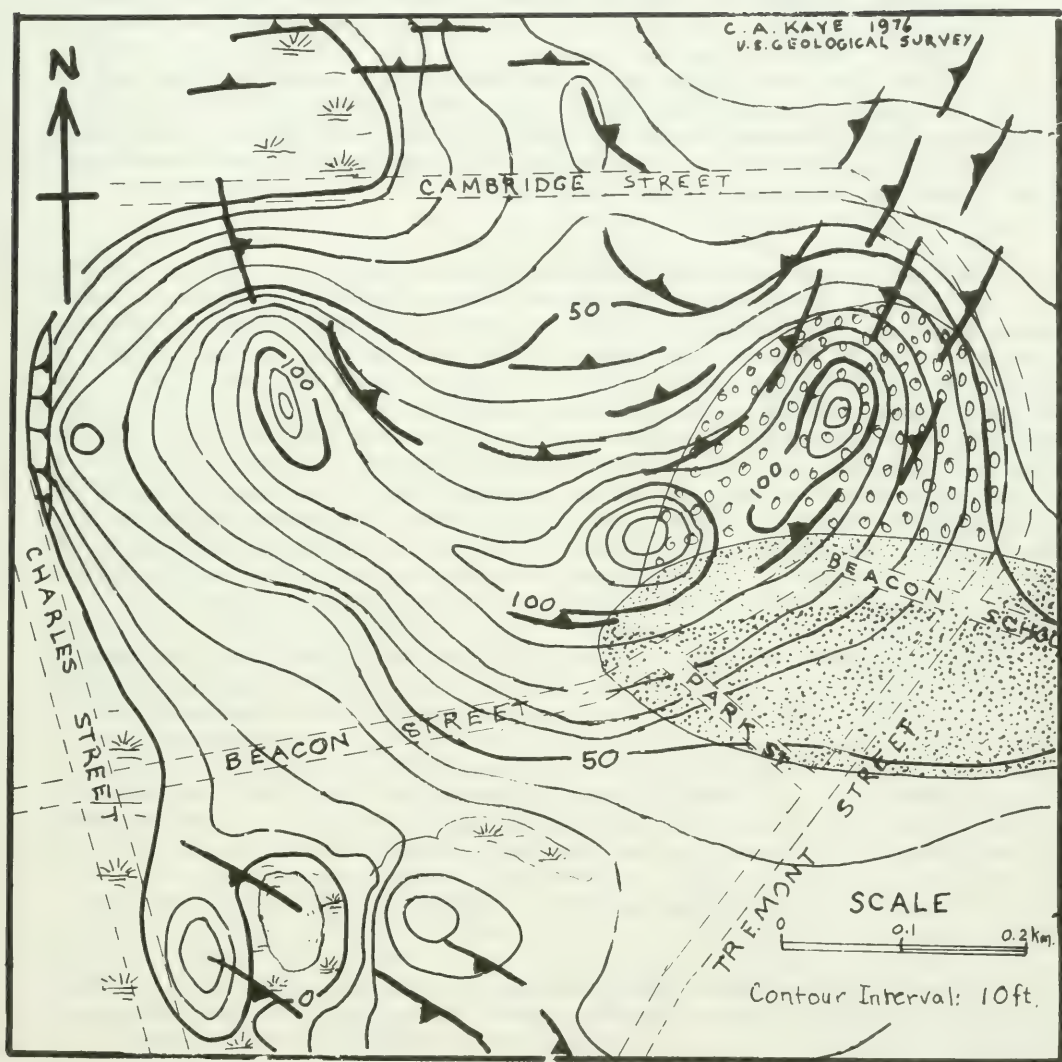Figure 2 – Reconstructed topography of Beacon Hill and Boston Common before artificial changes. Strikes and directions of dips of thrust plates and axial planes of overturned folds in Beacon Hill and Back Bay moraines are shown by heavy-line symbols. Data for western Beacon Hill inferred. Submoraine delta shown by open circles; submoraine section of drumlin by light stipple, drumlin outcrop by dark stipple.

During the past 15 years, excavations, mostly in the eastern part
of the hill, have exposed a complex of sand, gravel, clay and only minor
amounts of till. The deposits tend to be in thick sheets, or plates, often
separated by thrust faults. There are a variety of other kinds of structures
including folds, high-angle faults, diaper intrusions, etc.. The strike of
the thrust plates appears to conform to the arcuate shape of the original
hill's crestline and the dips are mainly northerly. The upper part of the
hill, at least, therefore appears to consist of a pile-up of large plates of
older sediment that must have been eroded and transported en bloc by the
glacial ice. The structure is a small version of what we see in the large
Gay Head moraine in western Martha's Vineyard (Kaye, 1964a). It is for this
reason that the upper part of Beacon Hill, née Trimount, is now considered
to be a segment of an end moraine that originally probably stretched
east and west across the Boston basin.

Exposed in the deep foundation excavations of the eastern end of the
hill are undeformed deposits that underlie the morainic accumulations and
therefore predate it. These consist of a small low drumlin (the south flank
of which crops out) and a large gravel delta that is built against the
north flank of the drumlin. The top of the delta is at altitude 10 m.
Bottomset sands and clays from the waterbody in which this delta formed
have been thrust up onto the top of the delta and are part of the overlying
moraine, along with still older gravel, sand, and till and clay. As
mentioned earlier, the stratigraphic arrangement in the moraine tends to be
inverted, with oldest deposits on top. This somewhat systematic glacial
sweeping into the Beacon Hill moraine therefore provides the geologist
with a rare opportunity to see a stratigraphy compressed into small compass
that otherwise would have been spread out and hidden from view.

Evidence for the moraine exists in submarine seismic profiles which
show thrust structures extending to the east, well out into Massachusetts
Bay. To the west of Beacon Hill, the moraine seems to have been small, and
it is possible that it was largely destroyed by glacial overriding. The
Fresh Pond moraine (Chute, 1959) in Cambridge, appears to be, in large part
at least, the work of a later glacial readvance, the Back Bay readvance
(below). One small section of moraine that possibly is part of the Beacon
Hill alignment is the Jamaica Pond moraine, situated about 5 km to the
southeast of Beacon Hill. This is a morainic head-of-outwash at the
northern outlet of a narrow bedrock valley which we shall see on the field
trip.

The age of the Beacon Hill readvance is certainly Wisconsin, probably
late Wisconsin. It is thought to be earlier than 14,000 C^{14} yrs. B.P. when
the fossiliferous marine clay in West Lynn was deposited. Tentatively I
suggest an age of about 20,000-17,000 C^{14} yrs. B.P., which seems to have been
the time when there was a major glacial surge to the west, down the axis of
the Narragansett Bay trough and yet when the Cape Cod Bay lobe had largely
melted.

The Clays

The marine clays that blanket the Maine coast extend as far south as the Boston basin. To the south of the Boston area these clays lie offshore but have not been found above sea level. Submarine seismic profiling shows that clay is widespread under Massachusetts and Cape Cod Bays, as well as in Boston harbor.

Boston "blue clay," as these clays are frequently called, is something of a misnomer for the color of unoxidized clay and silt is generally greenish gray, although bluish tints occur under sections of the Back Bay. Stratigraphically it is not one clay, however, but two, or very probably three.

The oldest of the 3 clays was seen in the older deposits in the Beacon Hill moraine. It is also found beneath the till, or interlayered with it in several drumlins. No fossils have been found and it is not known whether it is marine or freshwater in origin. Everywhere that it has been recognized it is very stiff and somewhat sandy. It may be the same horizon as that from which the shells in the drumlins came. The most widespread clay appears to be that associated with the 10 m deltas. The 10 m body of water in which these sediments were deposited appears to have been extensive. It possibly was largely freshwater at first, becoming brackish and finally oceanic as ice to the east and south wasted and a passage opened to the open ocean. Excavations in these clays show large lenticular masses of till. The larger till masses form drumlin-like hills.

No fossils have been found in these clays, perhaps reflecting a brackish or even fresh-water origin. Although the clay is commonly interbedded with fine sand, the fine color banding and graded bedding that is typical of laccustrine type varved clay is not present. Isolated pebbles and cobbles (dropstones) are fairly common.

Structurally, the bedding in these clays conforms to the topography on which the clays were deposited. This is in contrast to the youngest clay where bedding is generally horizontal. This characteristic is particularly marked on offshore seismic profiles.

The top 2-6 m of the clay has been oxidized yellow. The depth of oxidation appears to depend in part on texture, the finer grained clay exhibiting shallower oxidation, the more silty and sandy clays, deeper oxidation. This stiff yellow clay zone occurs even where the top of the clay is at elevations well below sea level, indicating that most of the oxidation took place during negative sea levels.

The youngest clay postdates the Beacon Hill moraine. It has been found to altitudes up to 15 m in the Boston area. This horizon has a sandy beach facies and the clay itself tends to be finer grained than the older clay. This clay is fossiliferous along the northern rim of the Boston basin, in the vicinity of Lynn, Revere, and Winthrop. The fauna consists of mollusks, barnacles, foraminifera and ostracods and is of a cold water type. Radiocarbon dating of fossil barnacle plates (5 dates) shows an average age of 14,000 C^{14} yrs. B.P.

Sea Levels

In discussing sea level, we must distinguish between eustatic sea level and relative sea level, or sea level in relation to some benchmark in the coastal zone. Relative sea level is a function mainly of vertical crustal movement in response to glacial loading or unloading and changes in eustatic sea level. It is the sea level we observe and measure directly.

Our data in the Boston area shows that relative sea level dropped steadily from about altitude 20 m at 14,000 C^{14}yrs. B.P. (our earliest date) to about altitude -20 m at 10,000 C^{14}yrs. B.P. (Kaye and Barghoorn, 1964). The trend was then reversed; and sea level slowly rose, attaining approximately present level about 2,000 C^{14}yrs. B.P.. Since then there appear to have been fluctuations of up to 1 m both above and below, probably largely the result of eustatic changes produced by world-wide temperature fluctuations.

Back Bay Readvance

Glacial ice seems to have occupied briefly much of the Boston basin after 14,000 C^{14}yrs. B.P.. Ice descended from the surrounding rim area via the major valleys and spread out as localized bulbous masses on the basin floor. One ice tongue flowed east through the Charles River valley and spread out over the area of the Back Bay. Another descended through the valley of the Mystic Lakes and occupied the Fresh Pond area in Cambridge (Chute, 1959). Both lobes were fed from a large stagnant relict ice cap that appears to have covered the uplands of eastern Massachusetts and Rhode Island and possibly New Hampshire as well in the years when the coastal lowlands were already ice-free and marine clay was being deposited.

Evidence for the Back Bay lobe was seen in excavations in the lower slopes of Beacon Hill and in the margins of the Back Bay. In the Beacon Hill area, the deformational structures consist of overturned folds and thrust faults that encircle the perimeter of the hill and are strongly discordant to the lobate trend of the Beacon Hill deformation (Fig. 2). In the excavation for the Common Garage, the direction of glacial deformation was to the northeast; on the north side of the hill, to the south. The Back Bay lobe appears to have squeezed up a low clay ridge at its southeastern margin to form Boston Neck, the narrow clay isthmus that was the only connection between Boston and the mainland in colonial times. In the Harvard Medical Schoool area at the southwestern margin of the lobe, clay was dragged up onto the 10 m delta. On the north side of the lobe in Cambridge, we find till and sheared clay up to altitudes of 17 m as a low, discontinuous ridge that curves around the Harvard University area and includes Dana Hill, Shady Hill, Observatory Hill, and Mount Auburn. In places, this ice lobe deposited as much as 10 m of till on top of the younger clays.

The ice lobe that flowed south out of the valley of the Mystic Lakes spread out in the basin that is now occupied by Fresh Pond. Its eastern limits have not been defined but this ice possibly was responsible for the till overlying clay that was noted by Marbut and Woodworth (1896) on Ten Pound Hill and other places along the lower valley of the Mystic River. This lobe almost coalesced with the Back Bay lobe along the line of Observatory Hill in Cambridge.

Cambridge Flood

Tne sudden melting of the residual ice cap and its lobate projections just described produced a rapid release of melt waters. In the Boston area, a flood of this origin came down the upper Charles River valley between present-day Newton, on the south, and Waltham and Watertown on the north. The flood was blocked by the remnant of the Back Bay lobe in the lower Charles River basin and, accordingly, was deflected north, across the low terrace of the area of Harvard University from whence it drained down the valley lying between the Shady Hill segment of the Back Bay moraine and the Somerville drumlins. The sands and gravels deposited by these floodwaters, which underlie the level plain on which most of Harvard stands, are current bedded towards this outlet.

Eolian Silt Blanket

Thin patches of soft fine sandy silt overlie the deposits of the Charles River flood and all other deposits in the area. This layer is rarely thicker than 1 m and generally is oxidized to an orange red color. It probably is a layer of windblown dust deposited at the last stage of glacial waning at a time when strong winds, blowing off the ice, picked up fine-grained sediment from the surface of the drift. This came to rest in peripheral areas, some of it perhaps trapped by grasses and low ground plants that were the vanguard of the spreading forests. The silt layer was once almost ubiquitous on the valley floors and lower slopes but owes its present patchy distribution to colonial and post-colonial man who dug it away, or allowed it to erode away, as a result of cultivation and grading.

Holocene

As sea level rose and flooded the Back Bay, silt and fine sand carried by the Charles River was deposited throughout the estuarine system. Along the channel of the river, coarser sands and gravels were laid down. The silts and fine sands of the backwaters have a high organic content as a result of the eutrophic nature of the estuarine system. During sea level rise and the deposition of these sediments, salt marshes rimmed the shore, building outward and upward (Kaye and Barghoorn, 1964). Buried in these

deposits is evidence of climatic and environmental changes (Johnson, 1943, 1949).

The greatest changes, of course, have occured since the coming of the machine age in the 19th century. Large-scale filling of the shoals and salt marshes of the estuarine system have changed the modest face of Boston. The filling of the Back Bay was the largest enterprise of this kind and was accomplished in a few decades during the Civil War and post-Civil War era (Whitehill, 1968). The fill consists mostly of outwash sands and gravels dug from the extensive deposits in the valley of the Charles River at Needham, about 15 miles upstream from Cambridge. This was carried to the Back Bay by railroad and dumped to form a network of street embankments.

Most recently the site of Logan Airport was reclaimed by means of hydraulic filling. This required dredging the late Pleistocene clays from nearby harbor bottom and confining the resulting clay slurry behind levees constructed for the purpose. In a few years time the clay had settled out by natural sedimentation and had built up a clay mat sufficient to support runways and the weight of the landing aircraft. Also included in the Logan Airport fill are two drumlins, Governors Island and Apple Island, that were leveled and are now completely covered by airport fill.

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A BIBLIOGRAPHY OF THESES, DISSERTATIONS AND HONORS PAPERS ON THE GEOLOGY OF EASTERN MASSACHUSETTS

THOMAS BREWER

This bibliography is an attempt to compile a listing of works concerning the geology of Eastern Massachusetts which have not been published, but which are available at the institutions where they were written. For this purpose, Eastern Massachusetts has been defined as the area east of and including the Connecticut Valley, or east of approximate longitude 72.6°. A few references have been included which appear relevant to Eastern Massachusetts problems although they have been written about field areas in adjoining states.

It is predictable that additional material (hopefully 1976 efforts) will appear after this listing is sent to the printer. With this in mind, I plan to print an additional page or two for distribution at conference registration. If you didn't get one, send a self addressed envelope to the address below, and I will see that one is mailed. Space has been left for additions at the bottom of each text page.

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My present intention is to update this list annually and to distribute it to area institutions. I have no doubt made errors or especially omissions. Corrections and additions are welcome. My thanks go the the individuals at area institutions who took the time to compile and send me their department's references. Special thanks go to John Mahoney and Barry Cameron from B.U. who made an initial compilation of much of this material.

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THE BOSTON BAY GROUP: THE BOULDER BED PROBLEM

by

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> "I wonder whether the boys who live in Roxbury and
> and Dorchester are ever moved to tears or filled with
> silent awe as they look upon the rocks and fragments
> of the "puddingstone" abounding in those localities.
> I have my suspicions that those boys "heave a stone"
> or "fire a brickbat," without any more tearful or
> philosophical contemplations than boys of less fav-
> ored regions expend on the same performance. Yet
> a lump of puddingstone is a thing to look at, to
> think about, to study over, to dream upon, to go crazy
> with, to beat one's brains out against."
> - Oliver Wendell Holmes
> The Professor at the
> Breakfast-table

The origin of the sedimentary rocks of the Boston Bay Group is one of the earliest and best known examples of the "boulder bed problem". The non-uniqueness of features common to sedimentary complexes of massive orthoconglomerates, diamictites, and rhythmically banded mudrocks has long been recognized in the Boston area (Sayles, 1914; Dott, 1961). This has given rise to two basic models for the sedimentation of the Boston Bay Group: as a glacio-alluvial-lacustrine complex; or as a complex of subaqueous gravity-transported sediment resulting from mass movements (grain flow, debris flow, and turbidity currents).

The Boston Bay Group has been divided into the Roxbury Conglomerate (which consists of three members, in ascending order; the Brookline Member, the Dorchester Member, and the Squantum Member) and the coeval and partly overlying Cambridge Argillite. Details of the lithology, thickness, bedding, and sedimentary structures of these units, from previous literature, are given in Table 1 and by Billings (this volume). The sedimentary rock types typical of these units are complexly intercalated, and their thicknesses vary greatly. Some workers have considered the stratigraphic subdivisions of the Roxbury Conglomerate unmappable but have retained them as a convenient descriptive framework (LaForge, 1932; Dott, 1961). Recent observations from water supply and drainage tunnels through the Boston Basin show that the Roxbury Conglomerate is a southern facies equivalent of the lower part of the Cambridge Argillite (Billings and Tierney, 1964; Billings, 1976 and this volume).

	Brookline Mbr.	Dorchester Mbr.	Squantum "Tillite" Mbr.	Cambridge Argillite
Thickness	500-4300'; thins rapidly to the southern margin of the basin	600-1600', generally approx. 1000'	70-600'	estimates have varied widely; minimums of 2000-4000'; from tunnel data, must be 7600' min. & may exceed 18,000'
Lithology	43-60% cong.; 20-55% argillite; 2-20% sandstone. Matrix: fine to medium feldspathic sand. Clasts: well-rounded, generally 1-3" with ave. 4"; locally up 12". Mostly quartzite, granite, felsite, lesser melaphyre and argillite; basal clasts coarser and typically of underlying formation. Interbedded volcanics	60% argillite, 25% sandstone; 15% conglomerate; 1% tuff. Fine to medium feldspathic sand; quartz grains rounded. Pebble clasts: mostly quartzite, some granite; lacks clasts of argillite; ave. max. pebble size of 5.5".	Diamictite, 50-63% matrix of silt and clay-size; locally sandy. Pebble clasts; subrounded to angular; rare striated, some faceted. Mostly of quartzite and granite, also felsite, argillite. Ave. 3-6"; but range to 2-3'; commonly; some to 20'. Some large angular argillite fragments bent and deformed.	fine-grained, mostly argillaceous (qtz.-sericite-chlorite); some siltstone and tuff; typically 90% argillite, 10% feldspathic sandstone; slightly calcareous.
Features of Current Deposition	Ripple marks and current bedding; (lamination and cross-bedding). Ripples generally oscillation type.	Cross-bedding common; ripple marks		common pinch and swell bedding in association with small-scale cross-bedding; oscillation and interference ripple marks (no current ripples) scour marks
Features of Gravity Deposition	Graded bedding		"dropstones" slump structures and contorted zones is the associated argillites	graded bedding; slump structures and contorted zones; load-casts
Bedding	Unbedded to obscure bedding; sand and shale partings and lenses; well-stratified in only a few places.	Absent or poor in the sandstones; argillite has well-stratified beds and lenses	Obscure or unstratified; associated thin sandstone and argillite layers.	rhythmic banding comprising about half of formation; beds generally 0.5-3"; pinch and swell in beds .25" thick
Other	Plant fossils (poorly preserved casts of tree-trunks)			color mostly gray to the north; 60% reddish to purplish & 40% gray or greenish to the south

Sources: Billings (1929,1976), Billings and Rahm (1966), Billings and Tierney (1964); Caldwell (1962).
Dott (1961), LaForge (1932), Rahm (1962), Sayles (1914)

Table 1. Description and lithology of the sedimentary formations and members of the Boston Bay Group.

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The Squantum "Tillite" occurs at a definite stratigraphic position at the top of the Roxbury Conglomerate throughout the southern part of the basin, although in a few localities it is represented by clast-supported roundstone conglomerates rather than the more typical open-work diamictite (Billings, 1976 and this volume).

The age of the Boston Bay Group still eludes us. The following ages and criteria have been suggested:

(1) Pennsylvanian to Permian; based on similarity in lithology and structural setting, and juxtiposition, to well-dated fossiliferous rocks of the Narragansett and Norfolk Basins (Billings, 1929, 1976; Sayles, 1914; LaForge, 1932).

(2) Upper Devonian to Permian; based on two poorly preserved tree trunks from the Brookline Member.

(3) Devonian to Mississippian; based on the presumed absence of Quincy granite pebbles from the Boston Bay Group rocks (Dott, 1961). Billings (1976) regards the question of the presence or absence of Quincy pebbles to be unresolved however.

(4) Several possible ages, based on different correlations of Brighton Volcanics of the Boston Bay Group to volcanics in fault contact with the group (Lynn-Mattapan) or possibly at the base of the Roxbury Conglomerate (Mattapan). These correlations permit an age of Devonian (if correlated to the fossil-bearing Newbury Volcanics to the north), Mississippian (based on doubtful fossils from the Mattapan Volcanics), or Pennsylvanian (if correlated to volcanics in the Narragansett Basin).

(5) Siluro-Ordovician; by analogy with regional glaciation in North Africa (Cameron et al., 1975).

Arguments can be made that the age of the Boston Bay Group is important to its tectonic setting, and is thus important to the depositional regime. As such, it is more comfortable to have a pre- or syn-Acadian age for a model involving gravity transport into a deep marine basin. A post-Acadian age would perhaps best correlate with a terrestrial (alluvial-lacustrine) model.

Dott (1961) attempted to refute the earlier supporters of glacial deposition of the Squantum "Tillite" and associated argillites (Sayles, 1914; LaForge, 1932) by showing that similar sedimentary characteristics can be produced by subaqueous debris flow and turbidity currents. Likewise, many of the features used in favor of mass movements (roundness of pebbles in the "tillite", relative rarity of striated pebbles, interfingering of lithologies, contorted and graded bedding in the argillites, etc.) are also characteristic of many tills and glacio-lacustrine deposits (Goldthwait, 1971). Debris flow and turbidity current processes can also be characteristic of a glacial setting; examples are flowtills, formed by debris

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flow off ice sheets, and glaciolacustrine rhythmites, formed
by turbidity currents either along ice contact margins of lakes
or off the mouths of inflowing streams (Gustavson, 1975).

Recent attempts have been made to solve the problem of
deposition of the Boston Bay Group, and the Squantum "Tillite"
in particular, by fabric and textural criteria. For example,
long-axis clast fabrics of the Squantum "Tillite" (Lindsay,
Summerson, and Barrett, 1970) are inferred to support a mud-
flow origin; but some long-axis orientations of Squantum clasts
also parallel the strike of the paleoslope, a feature not pre-
viously observed in mudflow fabrics. This fabric study involved
a highly sheared locality (Squantum Head), in which the clasts
could have undergone some tectonic rotation. Surface textures
on quartz sand grains from the Brookline Member and the
Squantum "Tillite" indicate glacial transport (Rehmer and
Hepburn, 1974), but such features can persist into extraglacial
environments for some time (or distance) before being
obliterated.

Much of the problem of interpreting the sedimentary rocks
of the Boston Bay Group stems from the fact that few facies
models have been developed for environments dominated by cong-
lomerates. The principal modern environments in which cong-
lomerates are accumulating today, and in which they could be
preserved, are: alluvial fans, braided rivers, shorelines,
deep sea submarine fans, and glacially-influenced areas (marine
and non-marine). Walker (1975, and in Harms et al., 1975) has
enumerated features to be observed in conglomerates and their
relationships to depositional environments, including: texture
(sorting, size distribution, clast vs. matrix support), fabric
of clasts, stratification, and grading (e.g., present or absent,
normal or inverse).

On this trip we will emphasize the dominantly clast-
supported conglomerates of the Brookline Member rather than
the matrix-supported Squantum "Tillite". Thick accumulations
of clast-supported conglomerate are possible in both fluvial
and deep-water[1] deposition (Harms et al., 1975). The coarse
clasts of the Roxbury Conglomerate are rarely graded, a char-
acteristic of fluvial or very proximal resedimented conglo-
merates. Stratification is also generally very obscure;
layers blend into each other without sharp boundaries, which
suggests fluctuating or pulsating depositional processes
(Harms et al., 1975). Flattened and elongate cobbles and peb-
bles are commonly oriented along bedding. Large conglomerate-
filled channels cut into underlying finer sediments have been

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[1] As "resedimented conglomerates", initially accumulated in
an unconsolidated pile in shallow water and subsequently
resedimented into deeper water; no transport mechanism
implied, but associated with turbidites (sense of Walker,
1975).

recently recognized by the authors in the vicinity of Hammond
Pond, Newton and may shed some light on the deposition of the
Brookline Member. Some of these channel conglomerates show
possible large-scale, low-angle cross-stratification (Stop 5A);
others reveal only a vague horizontal stratification (Stop 5D).

The finer sandstones, siltstones, and mudstones of the
Boston Bay Group display a variety of both gravity and current
depositional features including: current, oscillation, and
interference ripples; climbing ripples; large and small-scale
low-angle cross-stratification; scour and lag deposits; wavy
bedding of alternating sand and mud; isolated, "out-sized"
pebbles ("dropstones"); normal graded bedding; load casts; and
contorted bedding. It is well to remember that the surface
expression of the Boston Bay Group is strongly biased toward
the conglomerates. The more complete stratigraphic records
from tunnels (Tierney et al., 1968; Billings, this volume) show
that the less resistant sandstones and particularly argillites
make up a considerable portion of the Roxbury "Conglomerate".
The Cambridge Argillite, composed almost entirely of fine
sediments, outcrops particularly poorly.

A basic consensus can be reached on at least five points
relating to the Boston Bay deposits: (1) that the Cambridge
Argillite represents quiet-water deposition, (2) that the facies
change from dominantly conglomerate to dominantly argillite
(from south to north) is quite abrupt, and a source area to the
south is indicated, (3) that any depositional model must take
into account the difficult problem of the overlap of thick
argillite deposits onto the conglomerates, (4) that the group
is on the order of thousands of feet (hundreds of meters) thick,
and (5) that the diamictite (Squantum) at its type locality at
least, is bounded both above and below by the quiet-water
argillites. It seems to us that three basic depositional
models (and possible combinations of them) need to be considered:

(1) Terrestrial (Glacio-alluvial-lacustrine)

Cambridge Argillite is a lacustrine or glacio-lacustrine
deposit, possibly with some turbidity current deposition.

Squantum Mbr. is either a true tillite (ablation till over
lake), flow till, or subaerial debris flow; may be in part
alluvial where clast-supported. Most likely the result of
Alpine glaciation, if it is glacial.

Roxbury Conglomerate is predominantly alluvial or glacio-
alluvial (outwash). Braided stream deposits where clast-
supported with some possible glacial or debris flow where
matrix-supported. Some of the Dorchester Mbr. is probably
lacustrine.

(2) Marine mass movement in a eugeosynclinal setting (Dott, 1961)

Squantum Mbr. is a submarine debris flow of unknown water
depth.

Cambridge Argillite is marine; unknown water depth; turbidity current deposition implied.

Roxbury Conglomerate is either non-marine or very near shore (shoreline deposit); rapidly accumulated adjacent to volcanic or tectonically active land.

(3) <u>Subaqueous debris flow-subaqueous fan</u> (Modification of 2)

Squantum Mbr. is a subaqueous debris flow of unknown water depth.

Cambridge Argillite is a distal turbidite, partly reworked by weak bottom currents.

Roxbury Conglomerate is dominantly resedimented, with channel conglomerates in the inner fan and pebbly sandstones in the mid-fan area. Argillites and some sandstones in the Roxbury may be deposited on suprafan lobes or on the outer fan.

The major objections to the terrestrial model (Model 1) are: that the conglomerates of the Roxbury are too poorly sorted for typical alluvial deposits and are matrix-supported in some horizons; and that the thickness of the argillites (greater than 7500 ft.; see Table 1 and Billings, this volume) far exceeds known modern and ancient lake deposits. Greiner (1974) has described a fossil-bearing lacustrine rhythmite exceeding 4200 ft. (1300 m.) thick from a subsiding, post-Acadian (Mississippian) fault-bounded basin in New Brunswick; it is associated with terrestrial conglomerates and sandstones. Possibly a similar depositional environment existed in the Boston area at about the same time.

Problems with Models 2 and 3 are: the great abundance of both coarse and very fine clastics without sandstones typical of turbidites; the abundance of large-scale cross-bedding in the sandstones and possibly some conglomerates; and the almost complete absence of fossils. Clearly, the conglomerate-rich portion of the Boston Bay Group does not represent a classic fluxo-turbidite. The transgression of Cambridge onto Roxbury would tend to favor either moderately shallow water, or cessation of the high-energy conditions of the conglomerate deposition in a deep water environment.

ROAD LOG

Assemble at Boston University, parking lot G. Trip leaves at 8:30 A.M. The stops are in the Newton and Boston North 7.5' quadrangles.

Mileage
s/s   Cum.

| 0.0 | 0.0 | Road log begins at the south end of the Boston University Bridge across the Charles River. Cross bridge, heading north. |

0.2	0.2	Turn right onto Memorial Drive.
0.9	1.1	Bear left under Massachusetts Avenue.
0.2	1.3	Massachusetts Institute of Technology on the left.
0.4	1.7	Road branches, stay right on Memorial Drive.
0.7	2.4	Museum of Science on the right.
0.1	2.5	Turn left onto Mgr. McGrath Highway.
0.6	3.1	Enter Somerville.
0.4	3.5	Bear left, up onto ramp.
0.4	3.9	Bear right, onto Northern Artery of Mgr. McGrath Hwy.
0.1	4.0	Cross railroad tracks.
0.4	4.4	Major intersection with Broadway; continue straight.
0.3	4.7	Bear left, go beneath underpass.
0.3	5.0	Turn left onto Shore Drive at traffic light. Mystic River is on the right.
0.4	5.4	Continue under bridge and then turn left onto Mystic Avenue.
0.1	5.5	Turn right onto Butler Drive.
0.05	5.55	Turn right into housing project.
0.05	5.6	Turn left into parking lot.

Stop 1. Cambridge Argillite, at the old Mystic River Quarry, Somerville.

This outcrop is on the north limb of the Charles River Syncline and near shaft 9 of the City Tunnel Extension (Billings and Tierney, 1964). The argillite exposed here is in the lower part of the formation and is inferred to be coeval with the Brookline Mbr. of the Roxbury Conglomerate (Billings and Tierney, 1964). Beds trend N70°W, dipping 35°SW. The Cambridge Argillite has here been hornfelsed by greenish-gray felsic dikes that are well-exposed at both ends of the outcrop. Calcite veins occur along fractures in the dikes and adjacent argillite. Large pyrite crystals are present in the argillite near the dikes.

The Cambridge Argillite consists here of two rhythmically interlayered lithologies: dark gray to black, very fine-grained argillite comprising 60 to 70% of the sedimentary rocks present; and a lighter gray, fine-grained sandstone to siltstone comprising the remaining 30 to 40%. The sandstone beds are a few millimeters to 10 cm. thick, but are typically about 0.5 cm. thick. Many of these sandstone beds are graded.

Sedimentary structures, other than lamination, are not common in these rocks; but some of the sandstone beds appear to have erosional sole features (flutes or scours) and rare flame structures. Apparently ripped-up, very flat clasts of the darker pelitic material can be seen in some of the laminated sandstone beds. Slump folds, particularly well-exposed in the central part of the outcrop (just north of the fence), suggest that the bottom may have sloped westward. It is troublesome in this outcrop to unambiguously separate depositional sedimentary effects from those of penecontemporaneous or even tectonic deformation. Numerous small-scale faults cut the argillite.

Small-scale cross-beds and "pinch and swell" bedding are not seen in this outcrop. These are commonly associated features in other surface exposures of this formation, as well as in the tunnel exposures described by Billings and Tierney (1964) and Billings and Rahm (1966).

0.1	5.7	Leave parking lot and turn _right_ out of the road leading out of the housing project.
0.1	5.8	Turn _left_ onto Temple St. after first crossing over _Butler_ Street, which is _one way_ in the opposite direction.
0.1	5.9	Turn _right_ onto Mystic Avenue.
0.2	6.1	Turn _right_ onto Mgr. McGrath Hwy.
0.2	6.3	Intersection with Broadway; continue straight on McGrath Hwy.
0.2	6.5	Cross Pearl St.
0.2	6.7	Cross railroad tracks.
0.1	6.8	Bear _left_ onto McGrath Hwy.
0.4	7.2	Bear _left_, staying on McGrath Hwy.
0.4	7.6	Enter Cambridge.
0.6	8.2	Turn _right_ off McGrath Hwy., to Memorial Drive. Stay on Memorial Drive for the next 2.3 miles.
2.3	10.5	Turn _left_ onto Boston University Bridge; cross Charles River.
0.2	10.7	At the south end of the bridge, turn _right_ onto Commonwealth Avenue.
0.7	11.4	Intersection of Commonwealth and Brighton Ave. Continue straight.
0.6	12.0	Union Square; bear _left_ onto Cambridge St.
0.2	12.2	Turn _left_ onto Gordon St. at traffic light.

0.1 12.3 Exposures of Stop 2B on the left.

0.1 12.4 Entrance to parking lot. Park for Stops 2A and 2B.

Stop 2A. Dorchester Mbr. of the Roxbury Conglomerate; with Brighton Volcanics; Ringer Park, Allston (Figure 1). Please do not use your hammer in the park!

This outcrop is on the north flank of the Central Anticline. From the parking lot, head north to the outcrops of red, laminated argillites (Dorchester Mbr.) just inside the park. The thin beds (1 mm. to 1 cm.) with variable orientation (from N58°W, dipping 47°NE; to east-west, dipping 25-33°N; then to N38°E, dipping 34°NW as we walk northwest toward Gordon St.) are characterized by small-scale cross-bedding, ripples, and pinch and swell bedding. The paleocurrent direction here trends about N60°W. The red argillites are cut by intrusions of the Brighton, which can be better seen as you proceed to the top of the hill in the park. Minor faulting occurs in the argillite just to the left (south) of a small, younger trap dike.

As you walk up toward the summit of the hill, large xenolith blocks of the maroon siltstone and argillite are incorporated in and partly digested by the greenish, amygduloidal basalt. The volcanic rocks capping the hill are andesite to basalt, with abundant amygdules filled mostly with quartz and epidote. Although the volcanic rocks have been described as intrusive dikes and sills here (LaForge, 1932), they appear to be in part extrusive flows and ejecta as well. Some of the amygduloidal blocks appear to be pyroclastic bombs.
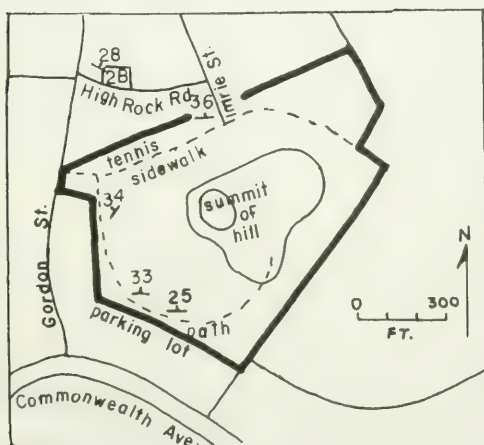
Figure 1. Location map of Ringer Park, Allston (outlined with heavy line), stops 2A and 2B.

Walk down the paved path to the playground. Outcrops of thinly bedded, alternating fine sandstone and argillite, without grading, can be seen adjacent to the basketball and tennis courts.

Exit tha park via Imbrie St. to High Rock Road. Continue past the first outcrop on the right, a massive greenish, epidote-rich basalt which contains layers of pyroclastic ejecta. Proceed to Stop 2B, the second outcrop on the right.

Stop 2B. This outcrop is on private property, so please do not use hammers or step on the flower beds.

The Dorchester Member here consists of a pinkish, feldspathic and lithic, medium- to coarse-grained sandstone with moderately well-sorted, subangular to subrounded grains. The slightly undulatory beds range from 8 to 30 cm. in thickness (typically 8 to 15 cm.). Finer partings of siltstone to very fine sandstone are only a few millimeters to about 3 cm. thick. Bedding is N65°W, dipping 28-32°NE.

Ripple-marked bedding planes are the prominant sedimentary structure to be seen in this outcrop. Both oscillation and interference ripples are present. The longer ripple crests trend N85°W and may be slightly asymmetrical, indicating transport from the north.

The sandstone is capped by dark green, amygduloidal volcanic rocks of the Brighton which have been interpreted in this outcrop as pyroclastic mudflow (lahar) deposits by Skehan (1975). Return to bus.

0.1	12.5	Leave parking lot and turn left onto Gordon St.
0.1	12.6	Turn right onto small street parallel to Commonwealth Ave. Then bear left at traffic light onto Commonwealth Avenue.
0.1-0.6	12.7-13.2	Small exposures of Roxbury Conglomerate on the right; red sandstone and argillite, with some conglomerate present.
0.5	13.7	Turn left onto Chestnut Hill Ave. at traffic light.
0.1	13.8	Cleveland Circle; turn right onto Beacon Street.
0.4	14.2	Chestnut Hill Pumping Station, eastern terminus of the City Tunnel (Tierney et al., 1968). Chestnut Hill Resevoir on the right.
0.5	14.7	Boston College on the right. The scarp separating the lower and upper campus is due to a N20°W-striking fault at the base of the slope, which separates Dorchester Mbr. to the east (lower campus) from Brookline Mbr. to the west (upper campus).

0.2	14.9	Entering Newton.
0.4	15.3	Outcrops of Brookline Mbr. of the Roxbury Conglomerate at the Mary Baker Eddy estate on the left.
0.3	15.6	Turn left onto Hammond Pond Parkway.
0.1	15.7	Pass Stop 5, on right.
0.3- 0.6	16.0- 16.3	Sandstones and conglomerates of the Brookline Mbr., at shallow dips near the axis of the Central Anticline.
0.4	16.7	Entering Brookline.
0.3	17.0	Brighton Volcanics on the left.
0.4	17.4	James Circle; rotary. Take second exit after entering the rotary, onto Newton St.
0.2	17.6	Brighton Volcanics and Roxbury Conglomerate exposed to the left, at the Putterham Meadows Golf Course.
0.3	17.9	Bear right, onto West Roxbury Parkway.
0.05- 0.1	17.95- 18.0	Outcrops of Brookline Mbr., here a clast-supported, roundstone boulder conglomerate, with clasts to 0.3 meters (1 ft.) common.
0.2	18.2	Francis X. Ryan Circle. Take second exit after entering the rotary and stay on West Roxbury Parkway.
0.2	18.4	Boulder conglomerate of the Brookline Mbr. on left.
0.2	18.6	Entering Boston.
0.1	18.7	Rotary. Take third exit after entering the rotary, onto Veterans of Foreign Wars Parkway.
0.8	19.5	Bear left.
0.1	19.6	Turn right onto Walter St. next to the Hebrew Rehabilitation Center.
0.1	19.7	Turn left onto Bussey St., entering the Arnold Arboretum grounds. Pull into the first entrance gate on the right. Take the path leading off to the left from the gate and proceed southeast up a small rise, for about 100 meters, to an old quarry in the Squantum "Tillite" Member of the Roxbury Conglomerate.

Stop 3. Squantum "Tillite", Arnold Arboretum, Boston.

Outcrops here and across Bussey St. are typical diamictite of the Squantum Member--obscurely bedded, matrix-supported polymictic conglomerate containing widely scattered clasts of considerable size range. The greenish-gray matrix is more clay-rich than that

of the typical Roxbury Conglomerate and has dev-
eloped an east-west foliation dipping 77°N. There
are larger, clear sand-sized grains in the matrix
at this locality that show surface textures typical
of glacial transport by electron microscopy (Rehmer
and Hepburn, 1974; Figure 2). The large clasts range
from completely angular "joint blocks" to rounded
pebbles to boulders. Boulders of 0.2 to 0.3 meters
are common, and sizes up to 1.0 meter in diameter
occur here. Clasts include felsite, granite, basalt,
quartzite, and argillite.

Return to bus.

0.1   19.8   Turn around and head back (west) on Bussey St.
             Turn right onto Walter St.

0.1   19.9   Turn left onto VFW Parkway at Piazza Square.

0.2   20.1   Bear right on VFW Parkway.

0.6   20.7   Rotary; make first exit after entering rotary
             onto West Roxbury Parkway.

0.5   21.2   Ryan Circle. Stay on West Roxbury Parkway
             (Second exit after entering the rotary).

0.3   21.5   Keep right at intersection (stay on West Rox-
             bury Parkway).

0.5   22.0   James Circle. Exit the second road (Hammond
             Pond Parkway) after entering the rotary.

0.8   22.8   Underpass of Route 9.

0.1   22.9   Turn right into Stearn's parking lot and proceed
             to the north end of the lot; park (Newton-
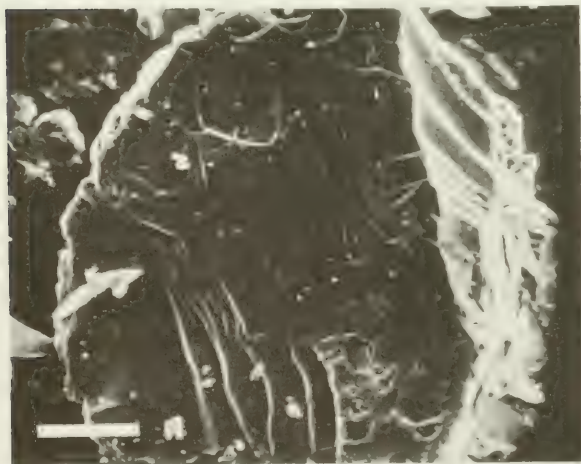   Webster Conservation Area).

Figure 2. SEM photo-
micrograph of an angular
quartz sand grain with
irregular flat surfaces
and jagged edges. Other
typical glacial features
include high relief, con-
choidal breakage blocks,
semiparallel and arc-
shaped steps; from Squantum
Mbr., Arnold Arboretum.
Bar scale = 50 microns.

<u>Stop 4</u>.   Lunch Stop, and Brookline Member of the Roxbury
          Conglomerate, Hammond Pond, Newton.

          The ledges here are typical Brookline Member--a
     massive, clast-supported, polymictic conglomerate
     containing well-rounded clasts predominantly of
     felsite, quartzite, and some granite. The matrix is
     a medium- to coarse-grained arkosic and lithic sand-
     stone. Bedding is obscure except for small, dis-
     continuous lenses of coarse sandstone and a rather
     poor alignment of pebbles and cobbles along bedding.
     Here, near the axis of the Central Anticline, the beds
     dip at low angles (10-20°).

          If time permits, walk northwest along Hammond
     Pond Parkway. A reddish sandstone with graded beds,
     some small-scale cross-stratification, and scattered
     isolated pebbles is seen to underlie the massive
     conglomerate.

          Freshly blasted exposures of the Brookline Mbr.
     can be seen in the parking lot of the Chestnut Hill
     Shopping Mall, west of the parkway, but please do not
     hammer here. Across from Bloomingdale's along the
     northeast side of the parking lot, nearly flat-lying
     fine- to medium-grained, pinkish sandstone with red
     shale interbeds overlies a conglomerate unit. Evi-
     dence of strong current action (cross-bedding, ripple
     marks, scour and fill) is abundant in these sand-
     stones. At the eastern end of the roadcut, a basaltic
     dike containing dark green chlorite, crysotile(?),
     and pyrite cuts across the sandstone, which has been
     hornfelsed by the intrusion.

0.1   23.0   Turn <u>right</u> onto Beacon Street.

0.85   23.85   Newton-Webster conservation area, Stop 5. We
               will probably turn around and park on the west
               (left) side of the road.

<u>Stop 5</u>.   Brookline Member of the Roxbury Conglomerate and
          Brighton Volcanics, Webster Conservation Area,
          Newton.

          The area of Stop 5 is shown in Figure 3. Expo-
     sures of the lower part of the Brookline Member of
     the Roxbury Conglomerate, in the woodland of the
     conservation area and along Beacon St. to the north,
     are the best in the Boston Basin for examining the
     sedimentological features of the roundstone-
     conglomerate facies of the Boston Bay Group. About
     110 meters (360 ft.) of section are present here.
     There are four intervals (CI-IV on Figures 3 and 4)
     of pebble/cobble conglomerate with intervals of
     sandstone and shale, and a nicely exposed 13 meter
     (±) lava flow (part of the Brighton Volcanics).
     The attitude of the beds here varies only slightly
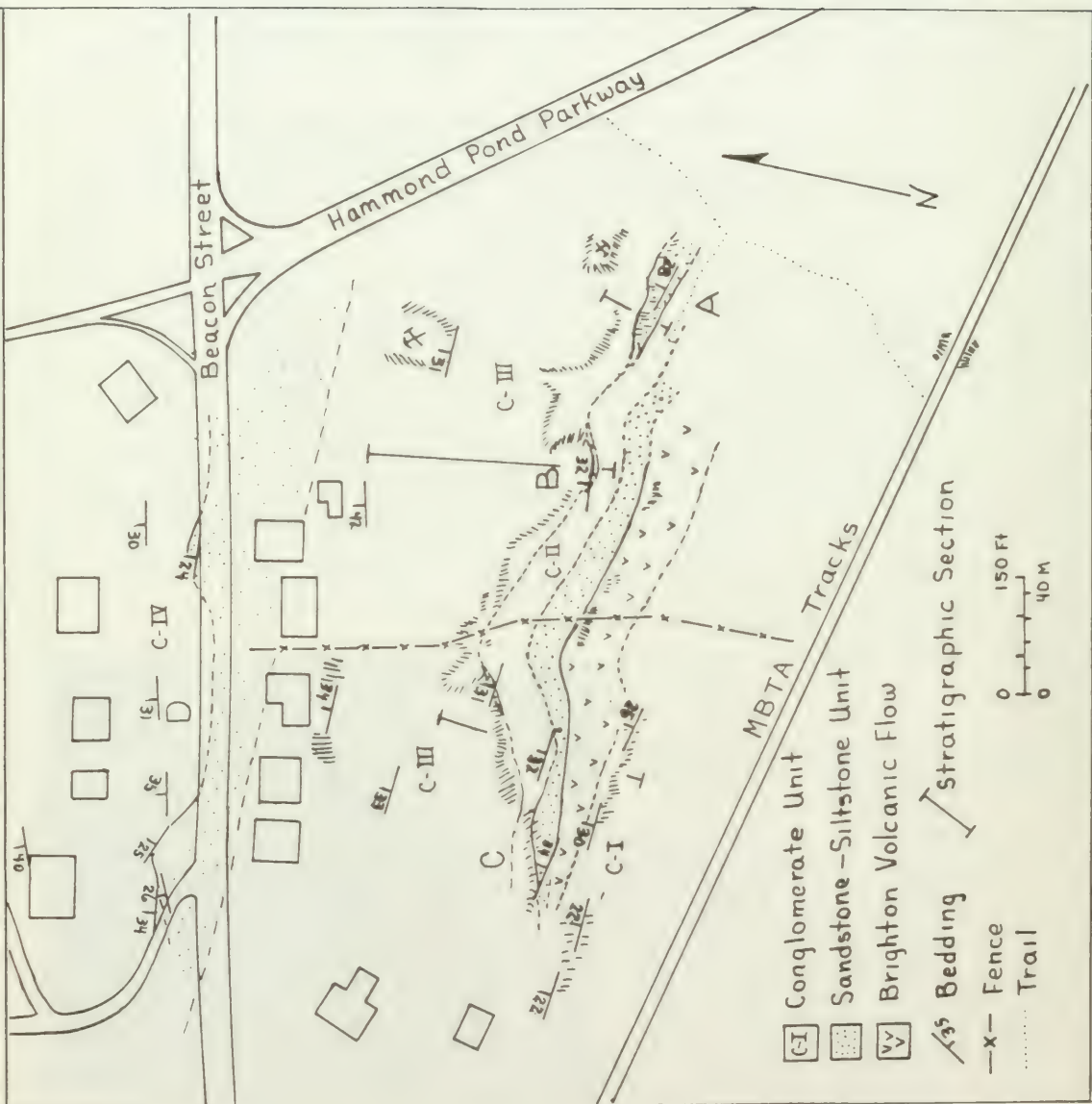
Figure 3. Geologic Map of Webster Conservation area, Newton (Stop 5), showing section lines of Figure 4.

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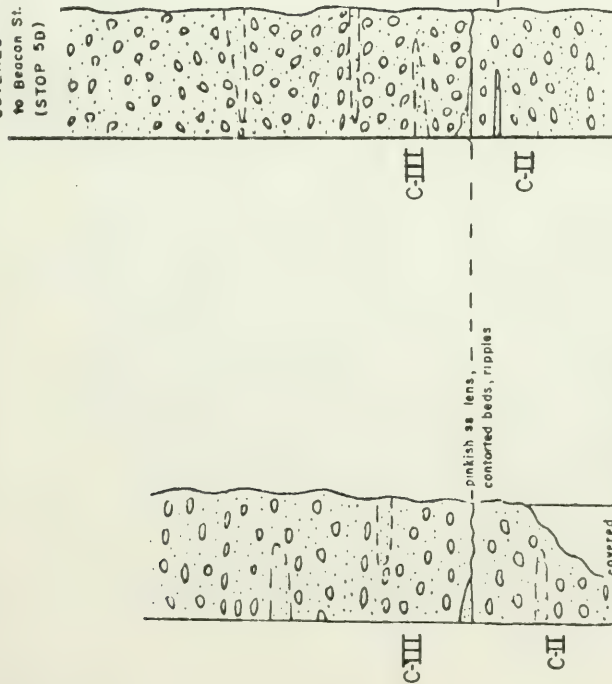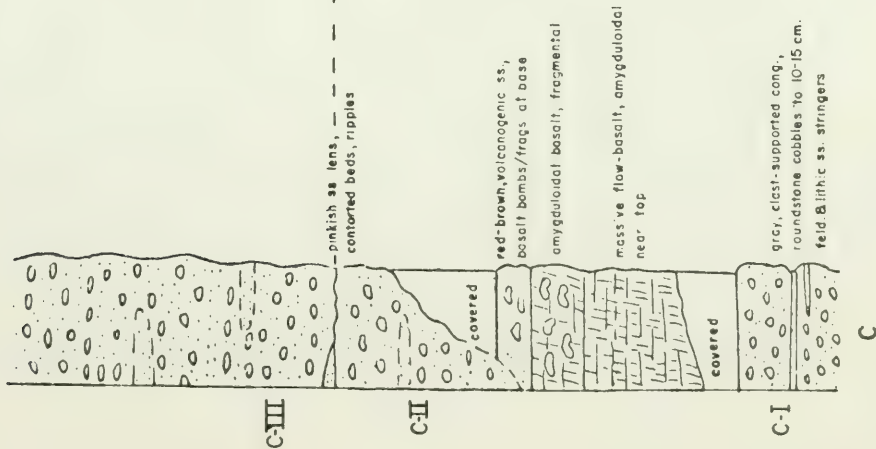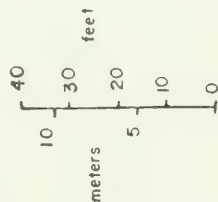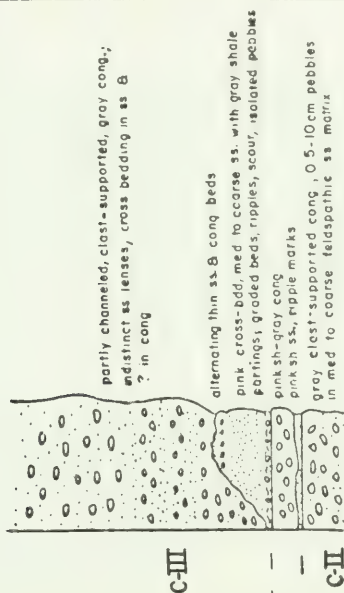
Figure 4. Generalized stratigraphic sections from west (area C) to east (area A) at the Webster Conservation Area, Newton (Stop 5). Sections in the Brookline Member of the Roxbury Conglomerate and the Brighton Volcanics.

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about an east-west strike and dips gently to the north at 25°-35°. The axis of the Central Anticline is 2 km. (1.3 mi.) to the south of these exposures.

We will begin this stop by examining areas A, B, and C (Figure 3) and then look at the exposures in area D on Beacon Street. Those of you who are allergic to poison ivy should be warned that it is almost ubiquitous around the exposures. In early October the leaves may be gone but the vines linger on, so be careful!

One spectacular feature of the succession here is the presence of erosional unconformities at the bases of the upper three conglomerate units (Figure 4). These unconformities have several meters of relief; and in three places (areas A, C, and D), the underlying sandstone-siltstone sequences are clearly truncated. Bedding within the channel conglomerates at areas A and D can be seen to abut laterally against the unconformity surface, suggesting that after deposition, the conglomerate sedimentation units had relatively flat upper surfaces. For example in area A, such a relatively thin (5 m.) conglomerate (C-II) is overlain by pebbly, lithic and feldspathic sandstones without an apparent surface of erosion.

In general, all of the conglomerate units contain well-rounded pebbles and cobbles of felsite (including rhyolite), quartzite, intermediate and mafic volcanics, granite, and pelite. Most of the conglomerate is clast-supported with a medium to coarse, lithic and feldspathic sandstone matrix. Stratification within the conglomerate is indicated by the presence of bedding orientation of tabular and elongate pebbles and by the presence of sandstone lenses. The sandstone lenses are typically less than 0.3 meters thick and may be traced laterally for a few meters (rarely up to about 20 meters). Some sandstone lenses are cross-bedded; many of the lenses do not have sharp bounding surfaces with the conglomerate. Where sandstone lenses are not abundant, the conglomerate units are difficult to subdivide. Intervals of conglomerate, uniform in texture, fabric, pebble composition, and size-range, but "broken" by sandstone lenses, are as much as 26 meters (85 ft.) thick (C-III). As defined by sandstone lenses, subunits of the conglomerate as thin as 0.3 meters and as thick as 2 to 3 meters apparently comprise the large intervals of conglomerate represented in Figures 3 and 4. Unconformities within the conglomerate units appear to be absent but may be merely cryptic due to the uniformity in texture and fabric of the conglomerates. One such cryptic unconformity is inferred at locality B, where conglomerate units II and III

are in contact. Reverse and normal grading within subunits of the conglomerate (between sandstone lenses, for example) has not been unambiguously established and, if present at all, is rare.

In area A, a well-exposed 4.6 meter sandstone-siltstone sequence is present between conglomerates II and III (Figure 4) and is cut out to the west. This succession contains lithic and feldspathic sandstone beds (a few centimeters to 0.6 meters thick), showing ripple marks, parallel lamination, ripple- and dune-scale cross-bedding, and graded bedding. Some isolated, "outsized" pebbles and cobbles occur within the sandstones, a few with overlying draped strata ("dropstones"). The ripples are especially well-exposed near the base of the sequence and are symmetrical to slightly asymmetrical. Although nearly symmetrical, these ripples may well be climbing ripples (type B of Jopling and Walker, 1968) rather than the wave ripples reported from the Brookline Member by Billings (this volume) and others. Slate beds up to 20 cm. thick are interlayered with the sandstone beds and extend in most cases for the length of the exposure.

In area C (Figure 3) the lava flow and overlying red-brown volcanogenic sandstone can be seen. The lower approximately 10 meters of the flow is massive; the upper part is highly amygduloidal and fragmental. The flow appears to have been of an aa-type with abundant rubble in its upper part. Large fragments of the flow are present at the base of the overlying sandstone.

After viewing the section exposed in areas A, B, and C, visit area D on the north side of Beacon Street. Please go to this area by way of the Hammond Pond Parkway rather than passing through private property. In area D, conglomerate unit IV rests unconformably on thinly laminated siltstone and fine sandstone (which probably also underlies Beacon St.). The thinly laminated siltstone, although never abundant, is commonly seen in surface exposures of the Brookline Mbr. in the Central Anticline. Here as elsewhere, this laminated siltstone displays strata-bound contorted beds with overturned to recumbent folds, which we believe to be the result of penecontemporaneous deformation. These folds are consistently over-turned to the northwest. Impressions of the siltstone bedding on the sole of the overlying conglomerate IV are visible locally at the west end of the exposure.

Although the stratigraphy here is, we think, reasonably represented by the map of Figure 3 and stratigraphic sections of Figure 4, many questions

are certainly unresolved concerning the modes of deposition involved in the formation of this sequence. Among these questions are:

(1) Do the thin lenses and interbeds of sandstone within the conglomerate represent depositional geometries, or are they the erosional remnants of once thicker and more areally extensive sand beds?

(2) Is the scale of channelling associated with the unconformities larger than that which we see on the scale of the outcrop? Namely, does each conglomerate unit (CI-CIV) fill a mega-channel at least as deep as the unit's exposed stratigraphic thickness; or is the conglomerate simply burying a previously eroded channel? We can see, for example, conglomerate-filled basal channels cut at least 15 meters deep and a few hundred meters wide into finer-grained sedimentary rocks. Are there also channels and scours within each conglomerate unit on the same scale, the margins of which are obscure because the substrate and channel fills are lithologically similar?

(3) Are the high-energy processes represented by both the cutting of channels (into sands and silts) and by the filling of these channels (by gravels) penecontemporaneous; or are the erosional and depositional events separated significantly in time?

(4) It is interesting to consider the role of extrusive volcanism in the development of this sequence. To what extent did the flows follow previously eroded channels? If glaciers were nearby as proposed by some, how might volcanism under or through the ice be in part responsible for what we see in the stratigraphy here?

Return to bus. Continue north on Hammond Pond Parkway.

0.1   23.95   Turn right onto Beacon St.

0.65   24.6   Enter Boston.

0.3   24.9   Turn left onto St. Thomas More Drive, then bear right onto Chestnut Hill Drive, around resevoir.

0.5   25.4   Park on the right, adjacent to Chestnut Hill Resevoir.

Stop 6.   Brookline Member of the Roxbury Conglomerate, Chestnut Hill Resevoir, Brighton. Access to the outcrops within the fence is normally restricted. Permission may be obtained from the Metropolitan District Commission. We will walk east from the gate for

about 350 meters along the gravel path adjacent
to the resevoir.

The outcrops of the Brookline Mbr. along the
shores of the resevoir are more poorly sorted and
less stratified than those seen previously at Stops
4 and 5. The conglomerate seen here have the
appearance of "disorganized beds" (sense of Walker,
1975). The cobbles and boulders are also larger
here; diameters of 15 cm. are common and can range
up to 0.3 meter. The clasts are of quartzite,
felsite, granite, melaphyre, and rarely conglomerate
and argillite. The outcrop adjacent to the rip-rap
blocks on the shore of the resevoir contain very
large blocks of red laminated siltstone and very
fine sandstone. One of these siltstone blocks
contains abundant, compressed, green reduction spots,
one of the few possible evidences of organic remains
in the Boston Bay Group (This feature has never been
seen in place).

The sandstone matrix is greenish-gray here. Rare,
thin lenses of sandstone within the more massive cong-
lomerates are the only good evidence of bedding in
these outcrops. The rocks trend east-west here and
dip to the north.

Return to bus. Continue east on Chestnut Hill Drive.

0.1   25.5   Turn right onto Commonwealth Avenue.

1.7   27.2   Intersection with Harvard St. Continue straight
               on Commonwealth Avenue.

0.3   27.5   Intersection with Brighton St. Continue on
               Commonwealth Avenue.

0.7   28.2   Intersection of Commonwealth Ave. and Essex St.
               (at south end of B.U. Bridge). Continue on
               Commonwealth Avenue to Boston University.

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Geology of the Squantum "Tillite"

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and Andrew Genes (Boston State College)

INTRODUCTION

The Squantum "Tillite" was first thoroughly described by R.W. Sayles in 1914. Since that time the unit has been restudied on several occasions by different workers and two conflicting modes of origin (glacial and subaqueous mass flow) have been favored. The exact age of the Squantum "Tillite" is indeterminate, but it is probably between Ordovician and Permian. We believe that any inferred evidence such as regional paleoclimatic conditions based on an assumed age for the Boston Basin should be used with caution. On this trip we will examine the field evidence that relates to the problem of the origin of the Squantum, and we will suggest several basin models that account for this evidence.

STRATIGRAPHY

Rocks within the Boston Basin (the Boston Bay Group) are divided into two major lithologic units. Roughly the northern half of the basin (north of the Charles River) consists of the Cambridge Argillite which overlies and is partially correlative with the Roxbury Conglomerate, exposed primarily in the southern half of the basin. The Roxbury Conglomerate is divided into three members, which, in ascending order, are the Brookline Member, the Dorchester Member, and the Squantum Member. Strata in the southern part of the basin rest unconformably on the Mattapan Volcanic Complex of Silurian-Devonian? age (Naylor & Sayre, this guidebook) and on the Dedham Quartz Monzonite of Precambrian age (Billings, 1976).

The upper and lower contacts of the Squantum Member are gradational. At several localities (Stops 6 and 7) gradational lithologies consisting of beds of sandstone, siltstone, mudstone, and pebbly mudstone are intercalated within the "tillite". Near the northern edge of the Roxbury Conglomerate, strata assigned to the Squantum consist of arkosic and lithic sandstones and clast supported conglomerates (Tierney and others, 1968). In some areas, Billings (1976) has assigned conglomerates at the appropriate stratigraphic position to the Squantum Member even though they do not have the typical "tillite" lithology. Thicknesses of the Squantum at different localities are given in Table 1. The Brookline - Dorchester - Squantum - Cambridge sequence occurs in the southern half of the main part of the Boston Basin and in a series of thrust fault slices (Fig. 1). Although these strike belts are separated, the Squantum is usually found in the proper stratigraphic position in each belt.

Table 1. Thickness of Squantum Member

| Locality	Thickness (m)	Notes	Reference
Main drainage tunnel	122	In lower part thinly laminated shales and scattered lenses of sandstone	Rahm, 1962
City tunnel	92	"Tillite" with 4 m thick bed of purple-gray argillite	Tierney, Billings and Cassidy, 1968
City tunnel extension	19	Cgl. bed with 2-20 cm sandstone lenses; Argillite above and below	Billings and Tierney, 1964
Hingham	41	Cgl. at proper stratigraphic position assigned to Squantum	Billings, 1976
Arnold Arboretum	135 (approximate)	Upper and lower contacts not exposed	See description for Stop 4
Squantum Head	134 (approximate)	"Tillite" bed exposed at Squantum Head only	See description for Stop 7
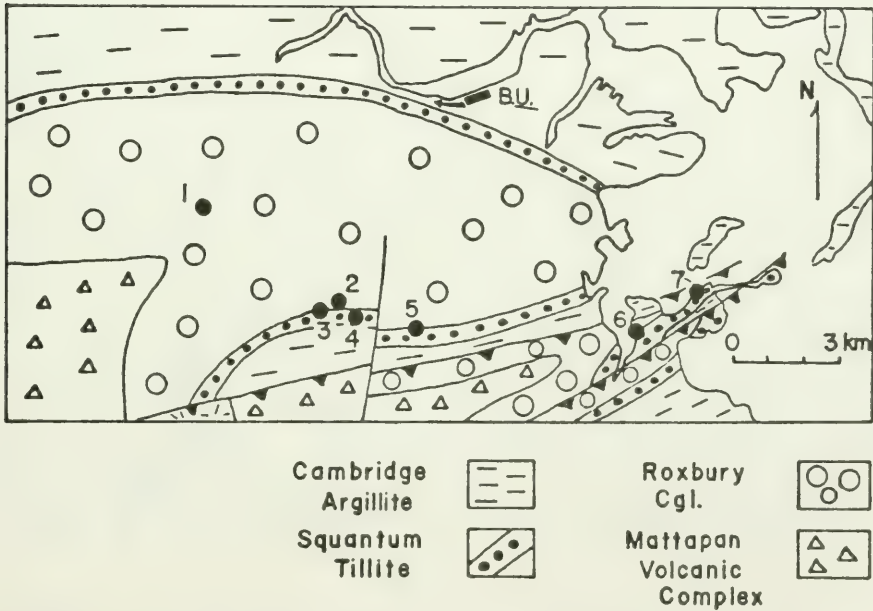
Figure. I Geologic map of a portion of the Boston Basin (from Billings, 1976) showing locations of field trip stops.

LITHOLOGIC DESCRIPTION

The Squantum Member is a polymictic paraconglomerate or a diamictite. The most distinctive characteristics are the poor sorting of clasts and the abundant sand-silt-clay matrix. Clasts range in size from several millimeters to slightly larger than one meter; however, most clasts are 2 to 30 cm in diameter. The Squantum generally has a matrix-supported texture, but clast-supported lenses and interbeds occur. Near the upper and lower contacts of the Squantum Member at the type locality (Stop 7, Squantum Head) the "tillite" grades into thinly laminated mudstones and siltstones. Outsized clasts, thinly graded sandstone beds, and pebbly layers occur within these thinly laminated mudstones. Large, deformed pieces of penecontemporaneously derived mudstone and siltstone (up to several meters in length) are found in the basal portion of the Squantum. Squantum clasts consist of rounded to sub-angular granites, quartzites, felsites, and flow-banded volcanics. Fragments of basalt, slate, and greenish to grayish siliceous argillite are present, but are not abundant.

A stretched-line technique was used to sample clasts from several localities in the Brookline and Squantum Members. This method entails recording the size and composition of each clast greater than 4 cm in diameter that is intersected by the line. An effort was made to select sample localities where plucking and differential weathering were minimal. Information gathered using the above technique is discussed below. Abundances of clast types (> 4 cm in diameter) from the Brookline and Squantum Members are shown in Figure 2. At most Squantum localities, felsite and volcanic clasts are dominant. Flow-bands and occasionally abundant vesicles characterize the volcanic clasts. The felsites are gray, brown, or red, and often contain quartz phenocrysts. Both the felsite and volcanic clasts could have been derived from the Mattapan Volcanic Complex, and/or the Brighton Volcanics. The Mattapan Volcanic Complex is exposed along the southern edge of the Boston Basin, and the Brighton Volcanics occur within the Roxbury Conglomerate. Volcanic activity and deposition of the Squantum may have been contemporaneous, but no direct evidence of such a relationship has been found. Figure 3 shows the relationship between mean clast diameter and standard deviation about the mean for different localities within the Squantum and Brookline Members. Clasts of the Brookline Member generally have slightly smaller mean diameters and are better sorted (with smaller standard deviations) than clasts from the Squantum Member. If these preliminary results can be sustained by further sampling, then an important constraint may be placed on the source material for the Squantum. Dott (1961) suggested that the Squantum Member might represent resedimented Brookline conglomerates. The Brookline Member is significantly different in texture from the Squantum, and therefore it is unlikely that Squantum clasts were derived from the Brookline. A basin edge facies of the Brookline Member, containing coarser clasts, might have been the source for the Squantum, but such a facies has not been preserved in the present Boston Basin.
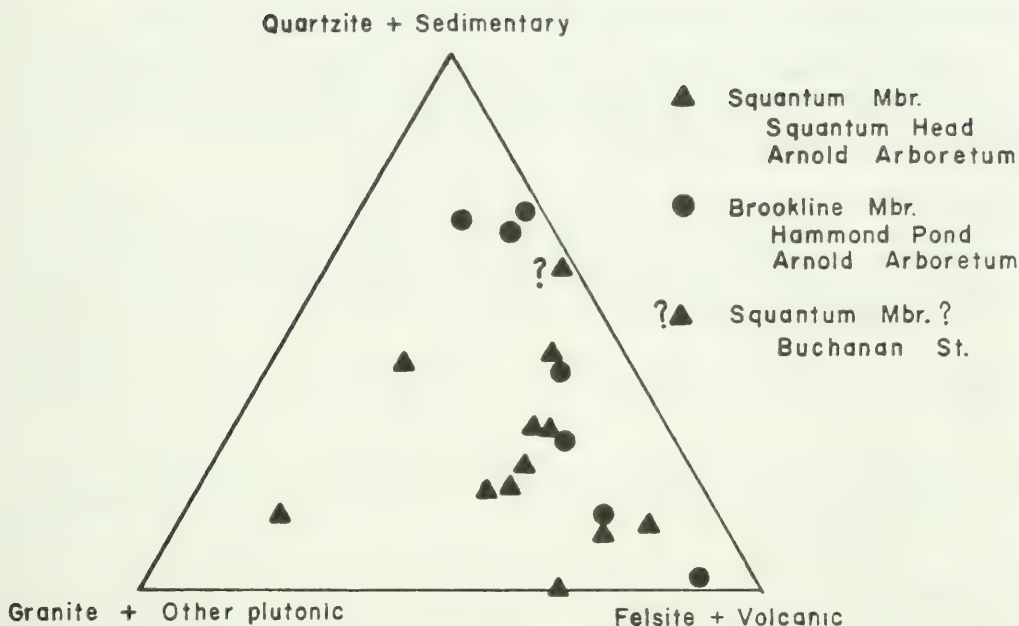
Figure 2. Abundances of clast types in the Squantum and Brookline Members.
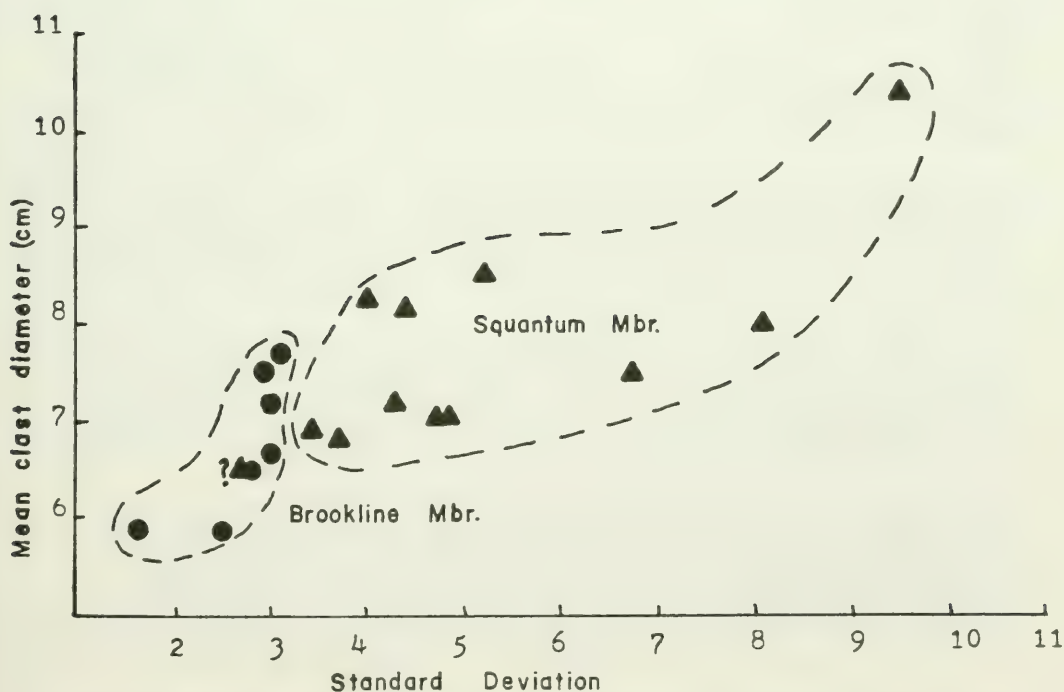
Figure 3. Mean clast diameter vs. standard deviation about mean, see Fig. 2 for meaning of symbols.

HISTORY OF SQUANTUM PROBLEM AND CONTRIBUTIONS OF PREVIOUS WORKERS

Contributions and opinions of some earlier workers as to the mode of origin of the Squantum "Tillite" are presented in the following section. No attempt has been made to make this an exhaustive list, but all major contributions are noted.

1. R.W. Sayles (1914) discussed in detail the origin and nature of the Squantum. He was strongly influenced by the poorly sorted, angular clasts (some with striations) occurring in a fine matrix. Sayles considered a mudflow origin, but rejected it in favor of a glacial one. He believed the Squantum Member was a tillite.

2. M.P. Billings (1929) noted the lithological similarity between the Squantum Member and Pleistocene till. He used the "tillite" as a key bed in his mapping of the Boston Basin.

3. L. LaForge (1932) considered the Squantum to be a tillite, but he noted the absence of the characteristic "tillite" lithology in some stratigraphic sections.

4. F.J. Pettijohn (1957) rejected as improbable a glacial origin for the Squantum and favored instead a subaqueous mudflow or turbidity flow mechanism. He cited graded beds, soft sediment deformational structures, and the lack of true ice-rafted clasts in the associated thinly laminated mudstones as evidence against glaciation.

5. R.H. Dott (1961) favored a subaqueous gravity mass-flow origin. He believed that there was more than one Squantum unit and that all of these units intertongued and were intergradational with the Brookline Member. Surface exposure was not adequate to allow him to test this hypothesis. Features such as graded bedding, absence of dropstones in the Cambridge Argillite, and the local origin of Squantum clasts were used as evidence in favor of a subaqueous mass flow.

6. D.W. Caldwell (1964) compared the roundness of clasts from the Squantum and Brookline Members. He found that mean roundness did not differ significantly, but that the roundness values were more variable (greater standard deviations) in the Squantum than in the Brookline.

7. J.F. Lindsay and others (1970) studied the clast fabric of the Squantum at Squantum Head. They concluded that clast orientations were similar to those normally found in a mudflow. The fabric was also found to be quite different from that of the Gowganda Formation, a Precambrian tillite.

8. J.A. Rehmer and J.C. Hepburn (1974) examined Squantum quartz grains with scanning electron microscopy. The microsurface textures they observed were similar to those reported from tills but dissimilar to those observed in mudflows. Quartz grains from the Brookline Member also showed "glacial" surface features.

9. M.P. Billings (1976) integrated subsurface geology of the Boston
    tunnels with surface geology to arrive at a logical and coherent
    framework for the structure and stratigraphy of the rocks of the
    Boston Basin. His work strongly indicates that the Squantum is a
    single unit at the top of the Roxbury Conglomerate.

BASIN MODELS

We believe that any idea invoked to explain the origin of the Squantum
should also be compatable with evidence seen in other rock units of the
basin. Three hypothetical basin models can account for the stratigraphic
relationships and sedimentary structures seen in the Squantum Member.
Each of the following models integrates much of the evidence, but each
model also has certain weaknesses.

I. Piedmont Glacial Model

During Squantum time a small piedmont glacier, originating from
valleys in a mountainous terrain immediately to the south, flowed into
the Boston Basin. Poorly sorted clasts, predominantly of local origin,
were transported across the southern edge of the basin and deposited as
till. Laminated sediments, deposited in proglacial lacustrine and
fluvial environments, were overridden by the advancing ice and incorporated
into the base of the till. Some of the ice-transported debris was
deposited by meltwater as sands and well-sorted clast-supported conglomerates.
Graded bedding was created when marginal deltaic sediments slumped into
proglacial lakes, thereby generating local small-scale turbidity flows.
The entire basin was non-marine. The Brookline Member represents a
fluvial environment and the Dorchester Member and Cambridge Argillite
represent lacustrine environments.

II. Subaqueous Mass Flow Model

The source material for the Squantum was transported by streams
flowing from a rugged source area to the south and initially deposited
at the edge of a subsiding marine or non-marine basin. Subaqueous mass
flows were generated when this material became unstable or when it was
shaken by seismic activity. These flows moved down the paleoslope to
the north. Most of the typical Squantum lithology represents resedimented
proximal (basin slope) conglomerates with abundant admixed sand, silt,
and clay. Previously deposited, thinly laminated turbidites (rhythmites)
were torn up and incorporated into the base of the mudflow. Some of the
sediment suspended by the flow continued further north into the basin
and was deposited as well-sorted conglomerates of turbidity current
channels or as graded sands and thinly laminated silts and muds. Portions
of the Brookline Member may represent clast-supported resedimented
conglomerates (Walker, 1975). The Cambridge Argillite represents a
"distal" turbidite deposited in the deepest part of the basin.

III. Floating Ice – Subaqueous Mass Flow Model

This hypothesis is similar to II above, except that a piedmont
glacier moved onto the edge of a marine basin or large bay. Glacially
transported sediments accumulated at the basin edge as ice floated into
the basin. Icebergs were calved at the floating margin of the glacier.
As these icebergs melted large clasts and pods of sediment fell to the

bottom. As in model II subaqueous mass flow transported sediment to
the north. A significant weakness of this model is that there is little
evidence for floating ice in the Boston Basin. True dropstones or
outsized clasts have not been reported or observed in the Dorchester
mudstones or the Cambridge Argillite. All outsized clasts to be seen
on this trip are found in pebbly mudstones immediately beneath the
Squantum.

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ITINERARY

Mileage

0.0   Trip mileage starts at the Charles Hayden Memorial Building
        705 Commonwealth Ave.; go east on Commonwealth Ave.

0.4   Kenmore Square; right on Brookline Ave. (second right at inter-
        section).

0.6   Fenway Park on left.

2.0   Right on Route 9 at stoplight.

3.2   Brookline reservoir on left.

4.8   Chestnut Hill Shopping Center on right.

5.1   Right on Hammond Pond Parkway immediately past R.H. Stearns
        department store (just before overpass).

5.2   Turn right into parking lot for Webster Conservation Area;
        Hammond Pond is to the NE of parking lot. Walk along trail to
        left (west) of pond about 100 yards, and up hill to left about
        50 yards. After examining outcrops on hill return to parking
        area, cross Hammond Pond Parkway, and walk up sidewalk to top
        of hill. Please be careful when crossing parkway.

STOP 1. Brookline Member, Hammond Pond

        The Brookline Member is a polymictic clast-supported conglomerate.
Bedding is often absent or poorly developed. Clasts, ranging in size
from 1 to 15 cm, are rounded to subrounded felsites, quartzites, and
granites. Coarse to fine, arkosic and lithic sand comprises the matrix
between clasts and also occurs as sandstone interbeds. The glaciated
and weathered outcrops on top of the hill to the west of Hammond Pond
show the relationships among clasts; however, the matrix and less
resistant clasts are difficult to study. Unweathered surfaces may be
examined in the roadcut along Hammond Pond Parkway. In this exposure
a 3.5 m thick sandstone bed is overlain by conglomerate. The lower part
of the sand bed is a coarse, arkosic, pebbly sand. The upper part is
a fine maroon sandstone. Crudely graded bedding is present in the
sandstone. Shale beds, 0.2 to 1 cm thick, are intercalated within the
sand beds. Dips of most beds in the vicinity of Hammond Pond are low;
the sandstone beds dip about 15° to the south. The conglomerate exposed
above and below the sandstone contains a variety of clasts, but red,
gray, and white felsites and quartzites dominate.

5.2   Turn left on Hammond Pond Parkway when leaving parking lot.

6.2   Enter Horace James Circle, go 180° around circle and bear right
       on Newton St.

6.7   Bear right on West Roxbury Parkway; outcrops of Brookline Mbr.
       on left.

7.0   Enter Thomas Ryan Circle, go 180° around circle and continue
       straight on West Roxbury Parkway.

7.6   Circle at intersection with VFW Parkway (Route 1), go 270° around
       circle and head toward Boston on VFW Parkway.

8.3   Intersection of Center St. and VFW Parkway (stoplight); stop 2
       is behind church to left but left turn cannot be made across VFW
       Parkway. Take left on Center St., about 0.1 mi. up hill reverse
       direction (U-turn) and return to intersection. Right on VFW
       Parkway. Go about 0.1 mi. and turn right into church parking
       lot. Park behind church in NW corner of lot. Walk up hill
       about 50 yards.

STOP 2. Brookline and Dorchester? Members, Cathedral of Our Lady of the
         Annunciation

         Near the base of the hill is exposed a pink to gray, thinly laminated
mudstone. This unit closely resembles the Dorchester Member that underlies
the Squantum Member at Squantum Head (stop 7). The mudstone at this
locality also underlies the Squantum which is exposed a short distance
to the south. About 20 yards up the hill the overlying Brookline Member
crops out. The contact between the Brookline and the Dorchester is not
well exposed behind the church, but it can be located to within one
meter by walking 100 yards to the west. This is an excellent locality
for collecting small-scale sedimentary structures as the mudstone contains
numerous small intrastratal folds ranging in amplitude from a few mm to
10 cm. The folding seems to be the result of loading a water saturated
muddy silt and of movement down a slight paleoslope. Very thin, poorly
graded beds are present in some samples. We consider this outcrop and
the next (stop 3) to be significant in that they demonstrate a stratigraphic
sequence in the vicinity of Arnold Arboretum that is very similar to the
sequence exposed at Atlantic (stop 6) and Squantum Head (stop 7).

8.3   Right on VFW Parkway, make U-turn across parkway or return to
       circle (about 0.6 mi.) and reverse direction; return to intersection
       of Center St. and VFW Pkwy. Right on Center St.

8.5   Right on Weld St.

8.6   Right on President St.

8.7   Right on Buchanan St.; park on right immediately after turning
       corner. Walk across street and to top of small knoll.

STOP 3.   Squantum Member?, Buchanan St.

    The glacially polished surface at the top of the small knoll
allows detailed study of the texture of a sorted, clast-supported
conglomerate near the base of the Squantum.   This conglomerate resembles
the Brookline Member, but it does contain several large clasts (the
largest being about 0.5 m in diameter).   Sandstone interbeds, up to 30 cm
in thickness, were fragmented and deformed while unconsolidated.
Subrounded to rounded felsite and quartzite fragments are abundant.

8.7   Continue straight on Buchanan St.

9.0   Left on Center St.

9.1   Intersection of Center St. and· VFW Parkway.

9.2   Right on Walter St.

9.3   Left into small parking lot at entrance gate to Arnold Arboretum.
       Enter gate and follow asphalt path about 300 yards to water
       fountain where path divides.   Climb evergreen covered ridge to
       right (south) and walk east along ridge.   Squantum is well
       exposed at easternmost end of ridge.   Walk west along ridge and
       return to gate.   Cross Bussey St., enter gate and walk to east
       (left) along low ridge for about 100 yards to an old quarry in
       the Squantum.

STOP 4.   Squantum Member, Arnold Arboretum

    The Squantum "tillite" Member in the Arboretum forms the ridges
to the north and south of Bussey St.   Note the small outcrops in the
streambed to your left as you walk along the paved path to examine
outcrops north of Bussey St.   The arkosic and quartzitic sandstones,
containing large granitic clasts, are near the base of the Squantum.
The Squantum is well exposed along the crest of the ridge to the right.
The best outcrops are at the eastern end of this ridge near a north
facing cliff, and in a small quarry 50 yards SW of the cliff.   Clasts
of all sizes occur in an abundant sand silt clay matrix.   Note the
well rounded quartzite clasts that are often weathered into relief.
Well rounded quartzite clasts suggest fluvial (?) transport prior to
resedimentation by ice or mudflow.   Rare deformed mudstone fragments
are present along the cliff face.   In the small quarry, the smaller
granitic clasts may be seen.   A large clast mold near the quarry is
one meter in diameter.

    The Squantum is exposed south of Bussey St. in an old quarry
and along a south facing bedrock slope 20 yards south of the quarry.
In this quarry, large angular to subrounded clasts occur in a silt-
sand matrix.   The matrix is coarser here than in outcrops north of
Bussey St. and contains large clear quartz grains that may represent
phenocrysts weathered from the Mattapan Volcanic Complex.   Clast-matrix
relationships may be observed on the weathered surface of the bedrock
slope south of the quarry.

9.3   Left on Walter St. and then an immediate left on Bussey St.

9.7   Left on South St. at stop sign.

10.4   South St. ends, Morton St. begins, continue straight on Morton
        St. under elevated railroad tracks.

10.7   Enter circle, Howard Johnsons on right; go less than 180° around
        circle and continue straight on Morton St. (Route 203-S).

11.2   Large outcrop of Brookline Conglomerate in Franklin Park.

11.5   Right on Cantebury St. Go 0.2 mi. and park on right side of
        road by fence. Cross road and walk about 75 yards to wooded
        hill behind dump.

STOP 5. Squantum Member, Canterbury St.

        A series of sandstone and conglomerate beds are exposed on the
western slopes of the wooded hill. Bedding is readily visible in the
southerly dipping conglomerates. Flat clasts are oriented with their
maximum axes parallel to bedding. Beds of well-sorted pebbly conglomerate
are intercalated within coarser, poorly sorted conglomerates. Conglomerates
near the top of the hill and on the south slope have a silt-sand matrix,
and are more poorly sorted.

        A short distance to the northwest of this locality, in Forest
Hills Cemetery, the only fossils (?) from the Boston Basin were collected
in the upper part of the Brookline Member. They are believed to be
casts of tree trunks, but due to their poor state of preservation an
accurate identification is not possible.

11.5   Return to Morton St., right on Morton St.

12.2   Cross Blue Hills Ave. at stoplight.

12.6   Cross railroad tracks.

12.9   Bear left on Gallivan Blvd. at sign indicating Route 203-S for
        Quincy and South Shore.

13.7   Cross Dorchester Blvd.

15.0   Intersection with Route 3 (southeast expressway). Past stoplight
        go straight under Route 3, bear right following signs for Route 3A
        to Quincy. Cross Neponset River Bridge. Stay in left lane which
        leads to Quincy Shore Drive.

15.3   Sign for Squantum, stay left on Quincy Shore Drive.

15.9   Left at light on Bay State Rd. (turn is across from large
        high-rise apt. complex). Go 0.2 mi. and turn left on Airport
        Rd. After less than 0.1 mi. enter gate to U.S. Navy housing.

FIGURE 4. STRATIGRAPHIC
SECTION AT ATLANTIC

N

BROOKLINE MBR.

50°

clast-supported cgl., clasts
5-10 cm in diameter, arkosic
and lithic sand matrix and
interbeds

cgl. with very angular gray
mudstone fragments

fence

gray mudstone with intrastratal
folds and thin pebbly sand beds

DORCHESTER MBR.

boulders stacked along road

fine to med. feldspathic
graded sands with cobbles
and boulders

60°

angular mudstone fragments

large laminated mudstone and
sandstone fragments, bent and
deformed

diamictite, silt-sand matrix

SQUANTUM MBR.

0   100 feet

Park in small lot immediately to left after entering gate. Walk
to west between houses and fence to western edge of peninsula.

STOP 6.   Brookline-Dorchester-Squantum Transition, Atlantic

        Dott (1961) studied this locality in great detail. Many of the
photographic figures in his Squantum paper illustrate sedimentary
structures at these outcrops. The transition from the Brookline to the
Dorchester to the Squantum is well exposed. Refer to the map (Fig. 4)
for the locations of structures and stratigraphic contacts. The
Brookline Member is composed of felsite clasts 1 to 8 cm in diameter.
Brookline conglomerates grade upward into lithic and arkosic pebbly sands,
and thinly laminated mudstones of the Dorchester Member. Many of the
mudstones display slump folds, deformed bedding, and penecontemporaneous
fragmentation. Large laminated, deformed mudstone fragments are found
near the base of the Squantum. The Squantum, exposed at the top of the
section, has large subangular to subrounded clasts in a maroon clay silt
matrix. This sequence demonstrates the gradational character of the
members comprising the Roxbury Conglomerate.

15.9   Return to intersection of Bay State Rd. and Quincy Shore Dr.
        Left on Quincy Shore Drive.

16.2   Left on Squantum St. at stoplight.

17.0   Bear left on Dorchester Ave.

17.4   Left into small dirt parking lot along fence. Walk to left (west)
        of fence along dirt path. Bear to left toward spit connecting
        concrete tower to mainland.

STOP 7.   Dorchester-Squantum-Cambridge, Squantum Head

        A complete section of the Squantum Member is exposed at the type
locality, as well as a portion of the underlying Dorchester Member and
the overlying Cambridge Argillite. Figure 5 summarizes the geology
exposed in the low cliff around Squantum Head and indicates the position
of important sedimentary structures and contacts. The gradational
contact between the Squantum and the underlying Dorchester is represented
by layers of pebbly mudstone interbedded with laminated mudstones and
fine sandstones. Large fragments of deformed mudstone are incorporated
into the base of the Squantum. "Dropstones" are usually present at the
base of the pebbly mudstones. These outsized clasts penetrate and deform
underlying thinly laminated mudstones. We have not observed a truly
isolated clast completely separated from pebbly layers. It is possible
that these "dropstones" could have slid or rolled into place, so we do
not consider them to be necessarily indicative of ice rafting. Along
the north side of Squantum Head an interval of thinly laminated mudstone
and sandstone (within the Squantum) has many intrastratal folds. The
Squantum Member is very heterogeneous. Sandstones and clast-supported
conglomerates occur. The dominant lithology is a matrix-rich conglomerate
which is often matrix-supported, containing very poorly sorted clasts.
Many of the clasts at this locality exceed 0.5 m in diameter and several

FIGURE 5. GEOLOGIC MAP OF SQUANTUM HEAD, MASS.

Portion of geology in cliffs; north side of Squantum Head

laminated mudstone with oatsized clasts

mudstone fragments

covered

slump folds

27 stack cave 26

1m quartzite boulder

100 feet

DORCHESTER MBR.

SQUANTUM MBR.

CAMBRIDGE ARGILLITE

SPIT
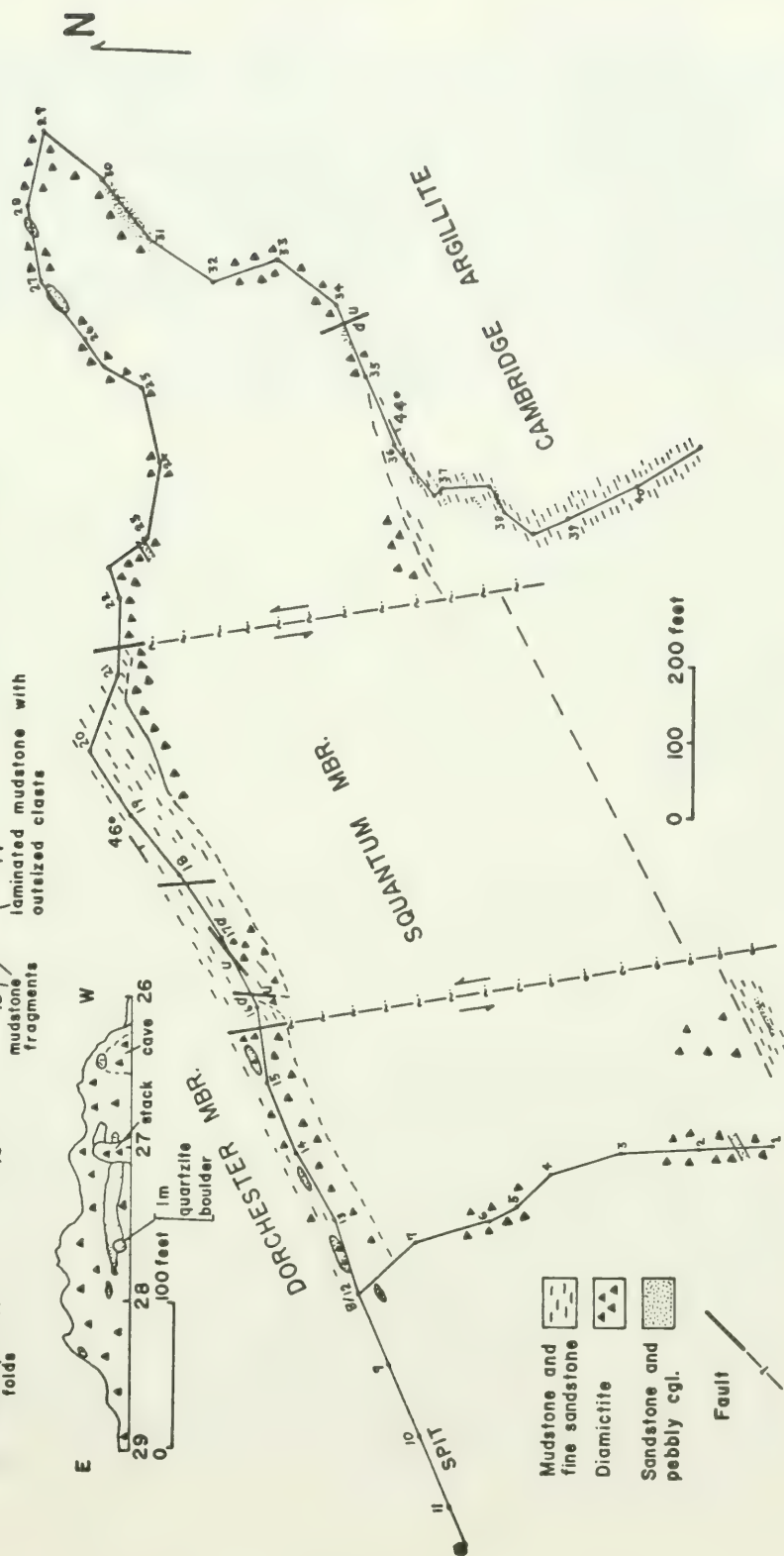
Mudstone and fine sandstone

Diamictite

Sandstone and pebbly cgl.

Fault

0   100   200 feet

N

105

are slightly greater than one meter. Felsites and flow-banded volcanic
clasts are dominant, but most large clasts are quartzites and granites.
We suggest that you start at the junction of the spit with the western
side of the headland and walk east and then south following the shoreline.
The traverse from west to east is roughly parallel to strike and allows
examination of the lower part of the Squantum and the upper part of the
Dorchester. The traverse to the south is normal to strike and permits
study of the variable Squantum lithology and the overlying Cambridge
Argillite. These traverses can only be fully accomplished at low tide.
After completing the traverses, climb the embankment to Dorchester St.
and walk west (right) to the parking area.

<div align="center">End of Trip</div>

GEOLOGY OF SQUAW HEAD,

SQUANTUM, MASS.

by

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Introduction.   No small compact area in the Boston Area provides such
a wide variety of geological phenomena for beginning and advanced students as
does the roughly 15 acre peninsula of Squaw Head on the northwestern side of
Squantum, a section of Quincy, Massachusetts. The lithology and stratigraphy,
the structure, the geomorphology of the region, and the historical evolution
of this unique area can serve to provide the basis for really extensive re-
search. Because of wave action and the susceptibility of the lithologies and
structures to rapid erosion, marked changes in the shoreline can be noted
even within a decade. The author has spent no less than fifty days in the
close study of this interesting area and continues to discover new phenomena
with each visit. Some of the changes over the past 35 years will be noted.

Lithology and stratigraphy

There is no point at this juncture in dwelling on the earlier works
dealing with Squaw Head. These have been adequately described and discussed
in a separate paper in this guidebook. Rather, I should like to dwell on the
total geology, as I see and interpret it. The pace and compass map which
accompanies this paper will refer to 38 points around the Head where inter-
esting geological phenomena can be noted.

The oldest rock unit is exposed on the northern shore. At very low tide,
when previous wave and undertow action have cleaned the wave cut terrace,
this rock unit can be seen as well bedded siltstone of an essentially varved
type with alternating layers of red-violet and light greenish colors with
average thicknesses of the layers varying from one to six millimeters. In
the upper three to five meters of this sequence masses of ill-sorted hetero-
geneous lenses of rock occur, with the longest directions of the lenses being
parallel to the strike of the beds in the region. The other major dimension
of the lenses is presumably parallel to the dip of the bedding of the under-
lying varves. A large quartzite boulder now rests in a pocket in the silt-
stone in the northwest corner of the Head. When the author first saw this 50
centimeter boulder, it was completely enclosed in the siltstone, except for
one small area of exposure. Wave action has released it from its matrix, but
it still rests in esentially the same position as when I first observed it
35 years ago. The upper two to three meters of the siltstone shows either no
stratification, or the stratification is obviously contorted, as at locality
14 shown on the map. Messy heterogeneous masses occur as distorted lenses in
this area.

The stratigraphy is not completely consistent throughout the north shore area of the Head, but for the most part the next stratigraphic unit is a completely heterogeneous mass. Rounded boulders as much as one meter in diameter occur, but these are rare. Boulders which approach 50 centimeters are common. Yet, there are many smaller clasts, most of which are rounded, but some are subangular. At least seven different lithologies can be seen in these pebbles and boulders. The matrix is sufficiently fine grained to facilitate the development of excellent cleavage in the matrix, cleavage which is equally as good as that in the underlying siltstone. There is probably nothing distinctive about this heterogeneous rock which can of itself rigorously define its origin. Comparable textures could be produced by glaciation, by mountain slope retreat in an arid region, by landslides, or by subaqueous slumping conditions. Essentially, there is no distinctive fabric for any of these rock types. Therefore, only by context mapping can one hope to establish the probable origin of the lithology. If one considers the total lithology and stratigraphy, as I shall show here, one is led very convincingly to the conclusion that the unit is of glacial origin; and the term Squantum Tillite is very apt.

One of the stratigraphic phenomena which supports this conclusion is the presence of well bedded sand and pebble beds within the body of the tillite. At stations 8,9,10 on the map as well as at station 24 this bedding is well exposed. The bedding is apparently alluvial in origin. In some of the finer beds at 9 and 10, three to four centimeter clasts, some of which are quite angular, are anomalously present. These could be explained in terms of small ice rafts moving out over an outwash region, and the bedded sandstones, pebble conglomerates, and even boulder conglomerates are to be best explained in terms of a frontal ice retreat with outwash developing in the foreground on top of the previously deposited till. In the northeastern section of the Head the conglomerate lens is as much as six meters thick, and this conglomerate lens is a notable part of the stratigraphy as far to the southwest as the quarry in the middle of the high ground near the directional arrow on the map. The presence of a sandstone-conglomerate member in the tillite suggests an oscillating ice front.

Stratigraphically above the tillite is a section which I have labelled a transition zone with a thickness of as much as ten meters. Lenses of completely heterogeneous material lie here and there within bedded siltstone. The bedding of the siltstone is deformed around these lenses, and there can be little doubt that they are till drops from ice rafts or icebergs moving out into the lake in which the varved siltstone was being deposited. The hill slope from the D in the word Head on the map down to the southeastern shore is essentially a dip slope in this transition zone material. The distribution of the till "drops" is best seen at stations 32, 33, 34. That the upper siltstone is not a repeat of the lower siltstone by means of an overturned fold, which might be inferred from the presence of the "drop" lenses below and above the tillite, is indicated by the absence of the highly disturbed zone near the upper contact. The bedding is not at all disturbed near the upper contact, as it is along the north shore in the lower contact region.

The uppermost unit in the Head area is again a bedded siltstone with varved properties. The overall grain size is slightly coarser in this rock unit than it is in the lower siltstone.

Three four inch basaltic dikes are occasionally observable at stations 36, 37, and 38. These strike approximately east-west and are vertical. An eight foot basaltic dike, striking roughly north-south, can be seen at 19. It is badly faulted and is accompanied by a ten centimeter quartz vein.

Glacial till of probable Wisconsin age rests upon the tillite in several places along the western and northern shores. The juxtaposition of Pleistocene till and Carboniferous (?) tillite is of interest. Possibly of more interest is the presence of Pleistocene glacial striations and polish on the Carboniferous(?) tillite at station 21.

Structure

The basic structure of the Head is of rock units striking between N45E and N70E and dipping 22 to 55 degrees southeastward. Such a structure could, of course, represent one limb of a fold; but I prefer to visualize the structure as a tilted fault block or tilted margin of a fault block. Faults are extremely common throughout the Boston region and in the Squantum region, making the last suggestion quite possible.

Cleavage is very well developed in the siltstones, with spacing between the cleavage planes of less than one millimeter wherever the rock has been exposed for more than a few years. The strike of the cleavage parallels that of the bedding planes, that is N45E to N70E, but the dip is generally perpendicular to the bedding dips, roughly 60 degrees in a northwesterly direction. Cleavage is well developed in the matrix of the tillite and helps to distinguish between the tillite and the conglomerate; the latter contains no silt size or smaller fractions and shows no cleavage.

Jointing is abundant in the rocks. The attitude of the joints is variable. Some of the joints parallel the obvious faults that occur in the rocks. Diamond shaped fragments are commonly developed between oblique joints and serve as susceptible zones of attack by wave action. In fact, the tillite and siltstones are particularly subject to wave quarrying because of their cleavage, joints, faults, and, in the siltstones, the bedding planes.

Faults are very common in the rocks. These are particularly obvious on the north shore. Most of the smaller displacement faults have not been plotted on the map, but faults are shown at localities 11, 12, 13 and 19-31. The dip of the faults varies from 60 degrees to vertical. The strike approximates north-south. A fault breccia zone at least 5 meters wide at station 11 serves as an area of rapid cliff retreat under wave action. The fault at this locality has a horizontal displacement of about 80 feet and is a normal fault. The horizontal displacement at locality 19 may be as much as 180 feet. Most of the faults have a right lateral displacement, and the block at locality 19 has been pushed southward to dictate the form of the shoreline. Mylonite and silicified gouge are common along many of the faults. A basalt dike which is itself highly faulted occupies the fault at locality 19. This suggests that much of the faulting was developed during the diastrophic phase which was accompanied by basalt dike formation, perhaps the Triassic episode. Many of the faults are occupied by quartz veins, varying in thickness from one centimeter to 10 centimeters, suggesting that the faulting was the result of uplift and extension. Some of the quartz veins are open in the middle and reveal well developed cockscomb crystals.

One of the very interesting aspects of the structure is the presence of extension fractures in the pebbles of the tillite. Although the attitude of these extension fractures is somewhat variable, they are usually about at right angles to the cleavage and are, therefore, nearly parallel to the bedding planes. Pebbles and boulders which vary in size from 2 to 60 centimeters may show these extension fractures. Many of the fractures are partially to completely filled with later quartz. Thus, the pebbles are somewhat elongated in the plane of the cleavage, not by plastic flow but by rupture.

Geomorphology

The most impressive aspect of the geomorphology of the area is the presence of the wave cut terrace at the base of a pronounced sea cliff. The terrace is best developed on the siltstone lithology where it may be considerably wider than 30 meters as exposed at low tide level. The terrace is best seen immediately following a northeastern storm when the undertow power is adequate to completely remove the usual clay that covers the lower part of the terrace. After a very heavy storm the entire terrace to the base of the sea cliff may be well exposed, showing a steeper upper profile and flatter lower profile. The smoothness of the terrace across the siltstone in spite of its abundant cleavage is remarkable. At the northeastern and eastern sections of the Head, the terrace is developed upon tillite and conglomerate and is much less flat. In fact, the existence of the jutting peninsula at the northeastern section of the Head is entirely due to the greater resistance of the conglomerate member to wave planation. The sea cliff at the head of the terrace varies from three to 16 meters in height. A classical example of a wave cut notch can be seen at locality 22. It occurs in a bedded conglomerate area and appears to be a very fragile phenomenon. However, no change has been seen in its profile during the past 35 years. In the Boston University lantern slide files is a picture which shows a car of vintage, roughly 1908, standing near the wave cut notch. No perceptible difference between the present notch and that of seventy years ago can be noted.

The trace of the cliff line on the northern shore is about 15 degrees to the east of the strike of the beds. This deviation is due to the presence of a series of right lateral faults which carry the resistant tillites ever farther southward as one proceeds eastward along the shore. The morphological expression of the faults is very noticeable, with variable indentations in the shoreline occurring at every fault. In the region of locality 11, as shown on the map, I have seen the cliff line retreat at least ten meters in the past 35 years. This particular fault is bordered by a fault breccia zone which is several meters in thickness.

The cliff line on the eastern shore to the south of the peninsula is shifted southward because of the 180 foot southward horizontal displacement of the tillite-lower siltstone contact. The cliff line recedes to the west on the eastern shore where the upper transition zone between the tillite and the upper siltstone occurs (station 32).

There are a series of terraces from sea level to the top of the hill in the midregion of the Head. The first terrace almost completely surrounds the head except for that area where the sea cliff of 16 meters has obliterated it. This lowest terrace lies at an elevation of three to four and one half meters.

A second terrace lies at an elevation of about 8 meters, and this terrace can be observed at several locations along the coast from Nantasket on the south to Marblehead on the north. In the Marblehead region this terrace is covered by Pleistocene glacial deposits which are presumably Wisconsin in age. Therefore the 8 meter terrace is preWisconsin and could well represent an interglacial still stand of sea level. Apparently, not much time is required to produce a terrace on these easily erodible rocks. The lower 4 meter terrace may well represent an oscillation of relative sea level in the past few thousand years, since clam shells have been found exposed in the soil lying on this terrace.

Steps in the topography can also be found at 13 meters and 20 meters. The top of the hill, which was certainly well glaciated during the Wisconsin ice invasion, lies at about 25 meters. This elevation is to be found at Nantasket and further north; and if this section of the coast is relatively stable, which it seems to be, the 25 meter level may well be the normal position of sea level during maximum deglaciation.

At locality 30, there is a mound of typical tillite surrounded by the 3 meter terrace. Just to the north of this former stack Wisconsin glacial striations and polish can be seen on the tillite. This clearly indicates that the plucking power of the glacier was relatively small. Capping the former stack is a smooth plane which is a remnant of the 8 meter terrace. Other stack-like masses inland toward the major hill also show this upper terrace level.

At low tide a beautiful spit extends from Thompson Island toward the head, and at the very lowest tides less than ten meters of water are exposed between the spit and the Head. This condition has been unchanged during the past 35 years; and it seems probable that this would-be tombolo is not going to join up with the head, due to the tidal currents which flow through the area in both directions with the shifting tides. The spit, however, has grown in elevation; and vegetation of salt water sedges has developed quite rapidly in the past 15 years. A major storm could reverse the process or even close the gap and allow a tombolo to form.

Geologic History

The geologic setting for the Squantum geology begins with the Acadian transformation of the Acadian geosyncline into a positively moving area. The usual history of a geosyncline as it moves from a negatively sinking area into a positively rising one is the uplift of a series of fault block mountains along steep angled reverse faults with the concomitant development of intermontane basins between the uplifting blocks. The Boston Basin region was one of these basins which probably developed at the close of the Devonian or very early in the Carboniferous. The evidence at hand suggests a major mountain block to the southeast of the Boston Basin with a wide intermontane basin to the north. A lake developed within this basin. Alluvial fans extended down from the mountain block into the basin, and these sediments interfingered with the simultaneously developing lacustrine sediments of the basin. The basic environment for the Roxbury conglomerate and Cambridge shale was thus set. The abundance of lithologies in the pebbles of the Roxbury Conglomerate suggests extensive alpine glaciation in the mountain block.

This suggestion is born out by the existence of the Squantum Tillite, the principle lithology at the head. A piedmont glacier began to move out over the gravel deposits. When the nose of the glacier reached the lake, icebergs carrying till and boulders floated out into the lake and dropped their loads on the lake deposits, as indicated by the boulders and messy lenses in the upper part of the lower siltstone. The glacier moved farther out into the lake. Occasionally, streams from the glacier would wash stratified materials into the lake, but soon the mass of the ice moved in over the lacustrine deposits and dropped materials and completely deformed them as indicated by the disappearance of bedding planes and the churned sediments at locality 14. After the glacier had stayed in the lake region for some time, the ice front receded, and streams once more moved out and deposited stratified materials of sand and conglomerate over the tillite. Once again the ice advanced, leaving several tens of meters more of till. As the ice withdrew from the region, icebergs once more carried till masses out and dropped them in the accumulating clays, forming the upper transition zone. The ice finally disappeared, and lacustrine deposits became dominant.

Faulting and dike intrusion may have taken place in the Triassic, and the Head sector probably was tilted about this time, developing the cleavage, extension fractures, and tilted bedding in one operation.

Wisconsin ice moved into the region and polished and striated the rocks, but some time before this four still stands of the ocean at levels of 3, 8, 13, 20 and 25 meters produced terraces in the easily erodible rock.

The Geology of Salient Points Around the Head

Locality 1. A 10 cm quartz vein, sometimes showing cockscomb, arrangement of quartz crystals, occupies a fault plane. Prominent shearing parallel to the fault walls is evidenced by the abundant cleavage in the adjacent tillite. A birch tree which now hangs from the side of the cliff was formerly well implanted on the 8 meter terrace just twenty years ago, indicating the rapid retreat of the cliff, even on this sheltered shoreline. Fault trends N85W and is vertical.

Locality 2. Another 10 cm quartz vein occupies a highly brecciated fault zone with well-defined mylonite defined in one section of the fault zone. Trend of the dike is N68W, and the fault is vertical.

Locality 3. Third fault showing indurated gouge layer 6 mm thick. Attitude of fault is N70W with 78 degree dip to north.

Locality 4. Interesting locality showing juxtaposition of Pleistocene till on Carboniferous (?) tillite. Note the comparable textures.

Locality 5. Very clean, planar jointing cuts through cobbles in tillite, indicating that jointing is post induration. If the tide is low, note the wave cut terrace which extends 70 meters outward from the cliff line.

Locality 6. Isolated two meter stack at high tide. A 50 cm boulder lies free in the midst of this lower siltstone outcrop. Thirty-five years ago, this boulder was just barely visible within the unbedded siltstone. Position of boulder suggests ice rafting from the approaching glacier which was moving into the lake.

Locality 7. Fault with attitude: N58W, 81°SW. The contact between a very messy tillite and disturbed siltstone can be seen here which probably represents contact disturbance between in moving glacier with its deposits and the underlying siltstone.

Locality 8. Good exposure of contact between tillite and siltstone. Several large tabular masses of iceberg dropped masses of heterogeneous material in siltstone. Contact attitude: N67E, 35°SE.

Locality 9. Well bedded stream deposited siltstone and sandstone showing small ice rafted pebbles; oscillating ice front withdrew and permitted some fluvioglacial activity and deposition.

Locality 10. Cast of large boulder in tillite; many such boulders have been removed by wave action during the past 35 years, and most of them have disappeared from the terrace by strong undertow action during heavy storms. Many of the pebbles and boulders show extension fracture cleavage which is roughly perpendicular to the cleavage in the tillite and parallel to the bedding planes in the adjacent siltstone. Beginning of fault zone with extreme brecciation through a breadth of about 16 meters.

Locality 11. Normal fault, N6E, 65°W. Right lateral displacement of contact between siltstone and tillite is roughly 80 feet.

Locality 12. Typical exposure of disturbed siltstone above well bedded siltstone, presumably produced by the advance of the glacial ice over the sediments of the lake bed. Marine terrace on the bedded siltstone extends more than 40 meters out to the position of low tide.

Locality 13. Another right lateral fault with silicified gouge. Shore becomes indented southward on the eastern side of the fault. Note the offset of the disturbed zone of the siltstone southward on the eastern block.

Locality 14. Excellent exposure of rolled beds of the upper siltstone. As the ice moved into this particular section of the lake bottom, the bedding planes were not destroyed, but they were severely deformed and rolled.

Locality 15. At this site there are some large masses of tillite at the base of the sea cliff. 35 years ago there was a large mass of rock attached to the cliff here except for one large joint. During one storm the entire mass was lifted and dropped perhaps 20 cm, but it was still resting against the wall. Through the succeeding years and storms the block has fragmented and the 4m X 4m X 1m block has been reduced to the present small residual blocks. Notice remnant of the 4m terrace above the sea cliff here. Just to the west, the sea cliff rises to an elevation of roughly 16 meters, and the lower terrace is obliterated.

Locality 16. The projecting cliff line here has retreated 8 m in the past 25 years. The excellent cleavage in the tillite plus faulting make the rock particularly susceptible to wave quarrying.

Locality 17. The deep recess or cave in this section is developing along a fault. The bottom sediments in this cave vary with each visit to the Head.

Locality 18. Sandstone bed here of ill sorted coarse sand grains formed during a recession of the ice front. It is a part of the rather extensive sandstone-conglomerate member which occurs in the tillite. Attitude: N45E, 38°SE.

Locality 19. Right lateral fault with a horizontal displacement of roughly 50 m is occupied by a messy basalt dike. The dike is itself faulted extensively, and a 10 cm quartz vein has occupied a part of the dike where later faulting took place. Just to the east about 10 m is a sandstone layer comparable to that at locality 18. Extending the two separated parts of this sandstone gives the approximate horizontal displacement of the fault. The 75 meter section east of the fault is displaced southward, but to the east of this block the rocks of the actual head are roughly on strike with the block to the west of the fault.

Locality 20. Very messy disturbed tillite and siltstone which was ostensibly formed at the interface between the inmoving glacier and the lake sediments.

Locality 21. Very interesting example of Pleistocene glacial polish and striations on Carboniferous (?) tillite. Glacier was moving S26E here; yet it was incompetent to move the isolated small stack like mass which stands above the 4 m terrace just 35 m to the south.

Locality 22. Classical example of a wave cut notch. From evidence at hand the general profile of this notch has not changed perceptibly in the past 70 years. The notch is incised in a messy conglomerate, rather than in tillite, which gives it greater resistance to wave destruction.

Locality 23. At low tide, wave cut terrace extends to narrow gut of water which separates Squaw Head from the spit which extends toward Squantum from Thompson Island. The channel is kept free of sediment by tidal currents which move in and out of the bay to the west. Mussel banks are growing steadily outward, and perhaps the spit will become a tombolo under very favorable circumstances.

Locality 24. Excellent exposure of well bedded pebble stone and cobble stone conglomerates. Cave at this point has been etched out along the fault which goes from one side of the head to the other.

Locality 25. Tremendous 1 m boulder in conglomerate, possibly explainable in terms of ice rafting on a proglacial stream. 4 m terrace surrounds about 2/3 of the Head which owes its existence to the conglomerate member.

Locality 26. Peninsula exists at this point because of the much greater resistance of the conglomerate member to the action of waves.

Locality 27. Large block bounded by joints has stood in this attitude without much change in position for the past 35 years. An exceedingly heavy storm could dislodge it, but such has not happened during the three and one half decades of observation.

Locality 28. Large masses of granite in tillite or conglomerate. Distinction is very difficult here. If the matrix is conglomerate the boulders must have been ice rafted to this spot.
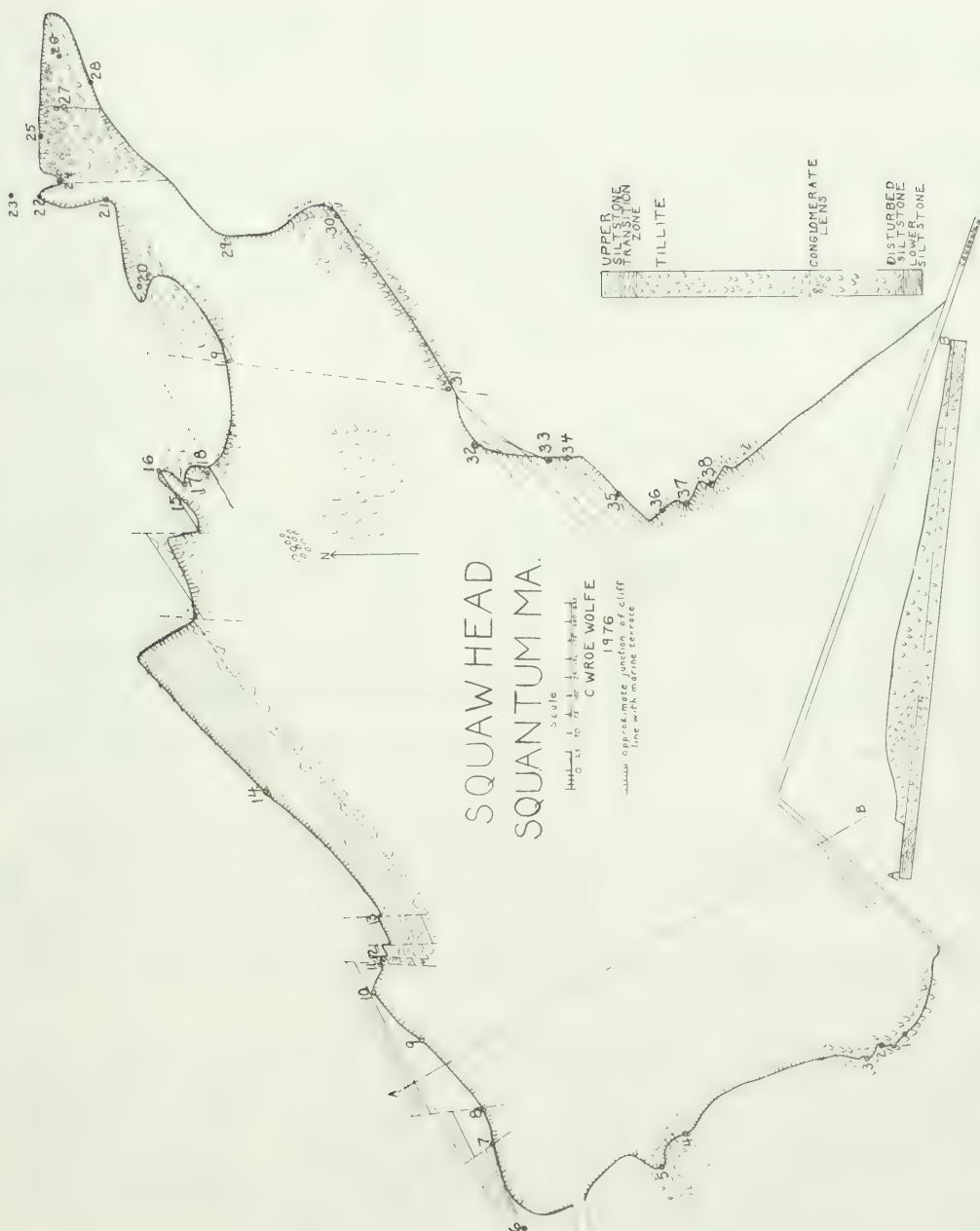
SQUAW HEAD
SQUANTUM MA.

Scale

C WROE WOLFE
1976

————— approximate junction of cliff
          line with marine terrace

UPPER
SILTSTONE
TRANSITION
ZONE

TILLITE

CONGLOMERATE
LENS

DISTURBED
SILTSTONE
LOWER
SILTSTONE

N

B

Location 29. Large summer hotel formerly sat here. Sedge grasses are beginning to anchor sediments here in the first stages of converting this part of the bay into a tidal marsh.

Locality 30. Classical example of tillite texture without any striated pebbles. Since most ground moraine of the Pleistocene glacier in New England does not contain soled and striated pebbles, the absence of these is not evidence for or against the glacial origin of the "tillite." Note the great variety of lithologies in the pebbles, which is more compatible with a glacial origin of the deposit than any other. 4 m terrace wraps around this rock mass which was a stack during the time the 4 m terrace was being carved. The top of this "stack" is very flat and may represent a residual of the old 8 m terrace.

Locality 31. The cliff line from 30 to 31 is formed on the southward moved tillite. Just to the west across the fault, the upper transition zone between tillite and upper siltstone is exposed.

Locality 32. Hill slope above this area is practically a dip slope of the upper transition zone. Here we see large pods of heterogeneous material interbedded with silt stone. Presumably, the glacier has retreated from this section of the lake, but icebergs continue to move out into the lake and to drop their loads of till.

Locality 33. Continuation of the transition lithologies upward but with a greater predominance of siltstone with occasional dropped pods.

Locality 34. Excellent dropped pods. Note overhanging tree, indicating the recession of the sea cliff even on this protected part of the Head.

Locality 35. Dip slope in siltstone. Quarrying into the dip slope has produced a pseudoanticline out of uniformly dipping beds. Note the marked coloring contrast between the violettish red beds and the light greenish beds.

Locality 36. Transition zone gives way to the upper siltstone without any further dropped pods. Presumably, the glacier has retreated too far to provide anything but rock flour to the lake.

Localities 37 and 38. Under proper exposure conditions two 10 cm basaltic dikes are occasionally exposed with east-west trends and vertical dips. The recesses in the cliff are developed where these dikes provide very little cohesion with the bounding siltstone. A very thin sediment cover extends out to low tide level and masks the bed rock marine terrace. The old terrace at 4 m is very marked in this section, simply because the earlier erosion could work so readily in the siltstone in this sector. In the distance note Moon Island, a drumlin, at the base of which on the northeast corner the till of the drumlin overlies an old erosion surface on conglomerate.

NEW EVIDENCE FOR GLACIATION DURING DEPOSITION

OF THE BOSTON BAY GROUP

by

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INTRODUCTION

Introduction:

The age, glacial origin and sedimentary environments of the rocks of the Boston Basin have long been a subject of much controversy. The exact age of the Boston Bay Group is indeterminable with fossils (Cameron and others, 1975) or radiometric methods (Naylor and Sayer, 1976), but recent opinions range from Ordovician to Permian. Resolving whether or not the well-known Squantum is a tillite or not is significant because it would represent the only well-documented glacially derived Paleozoic sedimentary rock in North America. The argument over the marine or lacustrine environment of deposition for some of the stratigraphic units, e. g., the Cambridge Argillite, is still unsettled. In our opinion, all three problems are related and the solution to one may lead to resolving the others. In this guide and on this field trip, we will argue for glaciation and lacustrine deposits in an intermontane basin of early Paleozoic age.

Boston Basin:

The Boston Basin is bounded on the north by a thrust fault and on the south by a series of _en echelon_ thrusts. The Boston Bay Group, which is over 17,000 feet thick, thins to the south, and is composed of the Cambridge Argillite whose lower half to the south changes facies into the Roxbury Conglomerate. The Roxbury is divided into three members which, in ascending order, are the Brookline Member (up to 4,700 feet thick), the Dorchester Member (up to 1,000 feet thick), and the Squantum Tillite (up to 400 feet thick). The source area of the conglomerates is to the south and southeast (Bell, 1948; Schneider, 1975; Billings, 1976; Jeanne, 1976). Along the southern border, the Roxbury appears to conformably overlay the Mattapan Volcanics (Caldwell, 1964) and unconformably overlay the late Precambrian Dedham Granodiorite (Naylor and Sayer, 1976). The Brookline Member also contains the Brighton Melaphyre (or Brighton Volcanic Complex), which is a discontinuous series of basaltic volcanics and dikes. These basinal rocks are characterized structurally by several east-northeast plunging folds and north-south and east-west trending faults (Billings, 1976). The degree of metamorphism is low-grade.

Age:

During the mid-19th century, the Boston Basin was considered to be of Cambrian age (LaForge, 1932), but the popular view changed to late Paleozoic when Burr and Burke (1900) reported poorly preserved tree trunks from the Roxbury Conglomerate. The proposed late Paleozoic age of the Boston Basin has been supported by (1) supposed lithic similarity with the known Pennsylvanian basins to the south, (2) two poorly preserved molds of tree trunks, which would indicate a range from Devonian to Permian, (3) a questionable fossil assemblage described

by Pollard (1965) as Mississippian and (4) correlation of the Squantum Tillite with known Permo-Carboniferous tillites of the Southern Hemisphere and India or the Gondwana continents.

This late Paleozoic age is not acceptable for the following reasons: The lithic and stratigraphic similarity with the Pennsylvanian Norfolk and Narragansett basins to the south are not convincing (Bell, 1948; Dott, 1961; Naylor and Sayer, 1976). The poorly preserved tree trunk-like molds could be cylindrical sandstone dikes such as those reported from Cambrian rocks in New York and Ontario (Shrock, 1948) (see "Clastic Dikes" section below). Pollard's (1965) ill-defined spiriferoid brachiopod and poorly preserved cortical and seed impressions in the Mattapan Volcanic Complex beneath the Roxbury resemble pseudofossils produced by inorganic processes and, as such, do not support a Mississippian age (Lyons, Tiffney, and Cameron, 1976). Paleoclimatic correlation with the southern late Paleozoic glaciations appears untenable because this region and supposedly adjacent northwest Africa, via plate tectonics, were within 10 or so degress of the late Paleozoic paleoequator.

A more tenable older Devonian age was suggested by Dott (1961). For different reasons, Naylor and Sayer (1976) also suggested a Devonian age. However, Cameron, Jeanne, and Schneider (1975) suggested an Ordovician-Silurian age based on correlation with the northwest African regional glaciation of that age. This hypothesis is supportable if New England and Africa were once joined during a "Wilson cycle" (Wilson, 1966).

Radiometric dating of the igneous rocks in and along the southern margin of of the Boston Basin has not been successful. Fairbairn and others (1966), using the Rb-Sr method, did not get a good isochron line for the Brighton Volcanic Complex. Although they could not draw any final conclusions, they suggested that the Roxbury Conglomerate may not be of late Paleozoic age, being possibly closer to the bottom than the top of the Era. Naylor and Sayer (1976) attribute the difficulty with using the Rb-Sr method in these rocks to their alkalic nature which allowed the labile ^{87}Sr to leave the rock system.

Glaciation:

The determination of the glacial origin of the Squantum by Sayles in 1909 and 1910 (LaForge, 1932) sparked a half century debate that still continues. Presently, many workers adhere to either a glacial origin or a subaqueous mudflow origin for the Squantum (Dott, 1961; Caldwell, 1964). The main reason for these alternatives is that a till and a mudflow have many features in common. Even the rhythmic banding in the Cambridge Argillite can be interpreted as either glacial lake varves or turbidites deposited by turbidity currents.

Besides the till-like appearance of the Squantum, other features suggest a glacial origin: dropstones (Rham, 1962), striated pebbles (Sayles, 1914), large angular clasts (Rham, 1962; Billings, 1976), and slump-like folds that could have been caused by the pressure of overriding ice. The associated Cambridge Argillite also has rhythmic banding resembling glacial lake varves.

Up until 1974, nobody seriously considered a glacial origin for any part of the Brookline Member of the Roxbury Conglomerate. However, Rehmer and Hepburn (1974) using scanning electron microscopy (SEM), reported glacial surface textural features on sand grains from both the Squantum Tillite and the Brookline Member. Cameron and others (1975) later reported possible dropstones, glacial(?) grooves,

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varve-like siltstones, and structures resembling ice wedging. These features contribute further evidence to strongly support the glacial history of the Boston Basin. It is such small-scale sedimentary evidence that we shall emphasize herein.

Sedimentary Environments:

From the discussions above several environmental models can be deduced for the Boston Basin. There is a consensus that the conglomerates of the Brookline Member are probably alluvial and were deposited close to a southern mountainous source. The Cambridge Argillite and the Dorchester Member in part represent quiet water deposition, either marine or lacustrine. The Squantum is either a submarine debris flow or a tillite, possibly deposited by an alpine type glacier. The "sandy" facies between the lower Cambridge Argillite and the Brookline Member may represent the paleoshoreline zone (Billings, 1976, Fig. 4).

EVIDENCE FOR GLACIATION

Introduction:

Because the outcrops to be examined on this trip are more or less along the axis of the eroded major eastward plunging fold in the Boston Basin, we will by studying the older rocks of the basin. Emphasis will be placed on the silt-stones and their contacts with sandstones and conglomerates. The siltstone in thin-section is a sandy, angular, fine matrix-rich silt which in places is fissile. The features that may, though not necessarily, be attributed to glacial activity include dropstones, varve-like bedding, grooves, and ice wedge-like structure, clastic dikes, and contorted beds.

Dropstones:

There is a total of one cobble and 6 pebbles which are excellent candidates for dropstones at two outcrops of siltstone (Fig. 1). Along the large Beacon Street outcrop (Stop #1) near the Hammond Pond Parkway, the eastern siltstone exposure (Fig. 2) contains a 7-7½" diameter cobble and a 1" diameter pebble in the same horizon. Five other pebbles in siltstone are found in the outcrop (Stop #2) behind the homeplate area of the Boston College baseball diamond. Four are in the same horizon and the fifth is in a layer one foot below them (Fig. 1).

These oversized clasts are interpreted to be dropstones because they are isolated in a much finer grained matrix. Apparently, they were rafted on the surface of a water body. If they were ice rafted, they could have been trans-ported by either bergs broken off a glacier or lake ice broken up and set free during a spring thaw. As the ice melted they were set free and settled to the bottom, depressing the underlying sediments that they settled upon. Later, deposited sediment draped over them. Being ice rafted, the rocks could be of any age, but if they were "tree rafted" they would have to be Devonian or younger. Ice rafted dropstones would certainly indicate a cold climate.

Varves:

The rhythmic banding in the Cambridge Argillite has long been considered to be glacial lake varves by many geologists (Caldwell, 1964). Some, however, would interpret them as turbidites (Dott, 1961). But, glacio-lacustrine sediments

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Figure 1

DROPSTONES IN SILTSTONES OF THE ROXBURY CONGLOMERATE

A   STOP I

laminations

cobble

8"

← 7" →

B   STOP I (to the left of A, same bed)

pebble

↕ "

← 1" →

C   STOP 2

pebble   pebble   P.

← 1" →

D   STOP 2 (12" below those in C)

pebble

← 1" →
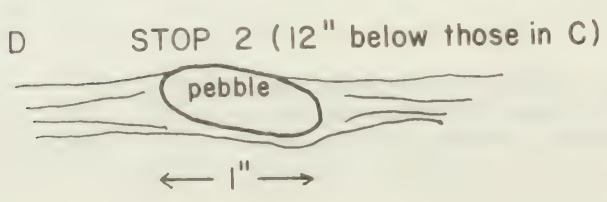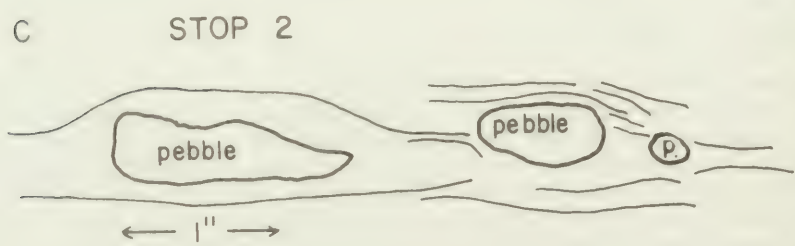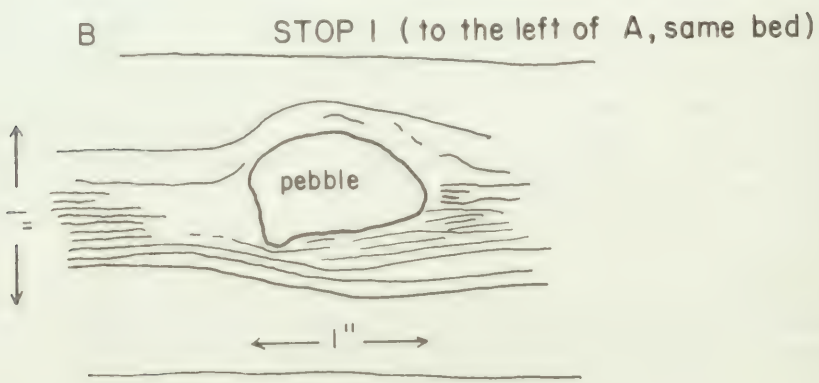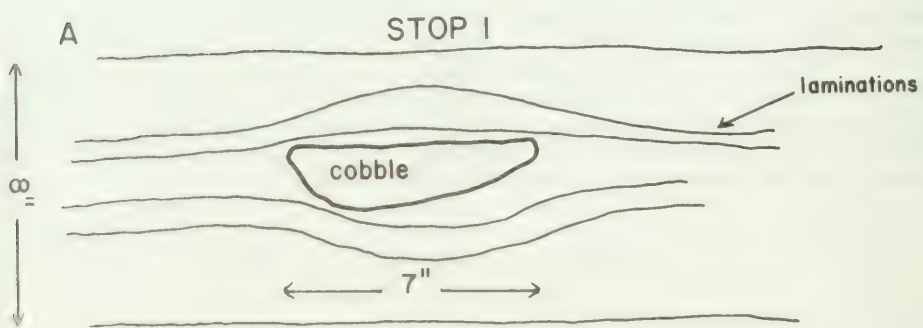
may develop alternating silt and clay layers due to turbidity currents (Harrison, 1975). Graded bedding, however, is rare in the Cambridge Argillite (Billings, 1976). The ubiquitous occurrence of these undisturbed, alternating light and dark bands indicates that burrowing organisms were not present possibly due to an unfavorably cold climate (Billings, 1976). An early to medial Paleozoic lake sequence would probably be unfossiliferous. Such varve-like sedimentary layering is present in the siltstone of the Brookline Member (Stops #1, 2, & 4). However, poorly developed varving, as is common here, is also found in such modern glacial lakes as Malaspina Lake in Alaska (Gustavson, 1975).

Grooves:

Several examples of grooves are visible on the Beacon Street outcrop (Stop #1) (Fig. 2). They vary from about 2 inches to over 2 feet across, trend northward, and are filled with conglomerate. These could be glacial grooves or due to alluvial channelling.

This surface separating the siltstone and conglomerate has been considered an unconformity (Wadsworth, 1882; Skehan, 1975), but others have considered it to be a thrust fault (Mansfield, 1906; LaForge, 1932). However, in places the siltstone grades upward into a sandstone which, in turn, grades upward into the conglomerate (Fig. 2). Although the siltstone laminations are often truncated by erosion, there is probably no major temporal break in the section. Rather, the irregular contact and grooves could have been caused by fluvial channelling or glacial scouring in a proglacial or piedmont environment.

Dott (1961) pointed out the lack of a striated pavement for support of the glacial origin of the Squantum Tillite. However, these grooves within the "soft" Brookline Member, rather than at the base of the Boston Bay Group, may possibly represent such a pavement. The two siltstone masses on Beacon Street may even be "highs" on a deeply grooved surface. Such large grooves are possible in such a "soft" substrate as a siltstone (Flint, 1971). An alternative interpretation is that these grooves were made by broken up ice blocks scratching the surface of a tidal mudflat when being carried seaward by ebb tide currents (Dionne, 1972). However, there is no evidence to support a marine environment for any part of the Boston Bay Group.

Ice Wedging Structure:

A "V"-shaped vertical crack at the top of the siltstone which is filled with sandstone and conglomerate occurs at the Beacon Street outcrop (Fig. 2). The siltstone laminations on either side are folded and some are broken by a fault on the west side. Such a structure could have been produced in a permafrost environment where ice in cracks expands and deforms the surrounding sediment. Large exposed surfaces are not available to search for polygonal ground patterns formed by cracks in which ice wedges form.

Contorted Laminations:

Contorted laminations have been reported from the Cambridge Argillite and the Squantum Tillite. These irregular folds may be drag folds, penecontemporaneous slumps in lake or marine waters, or intraformational slumps, but they may also be due to the pressure of glacial ice overriding lake bottom sediments. Even if they are just penecontemporaneous slumps and slump-folds, such deforma-

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Figure 2

BEACON ST. OUTCROP OF BROOKLINE MEMBER OF THE

ROXBURY CONGLOMERATE

KEY

ⓓ = dropstones(?)
g = groove
iw = ice wedge(?)structure
ssd = sandstone dike
f = folds
v = well-developed varves
n2°w = direction of grooves
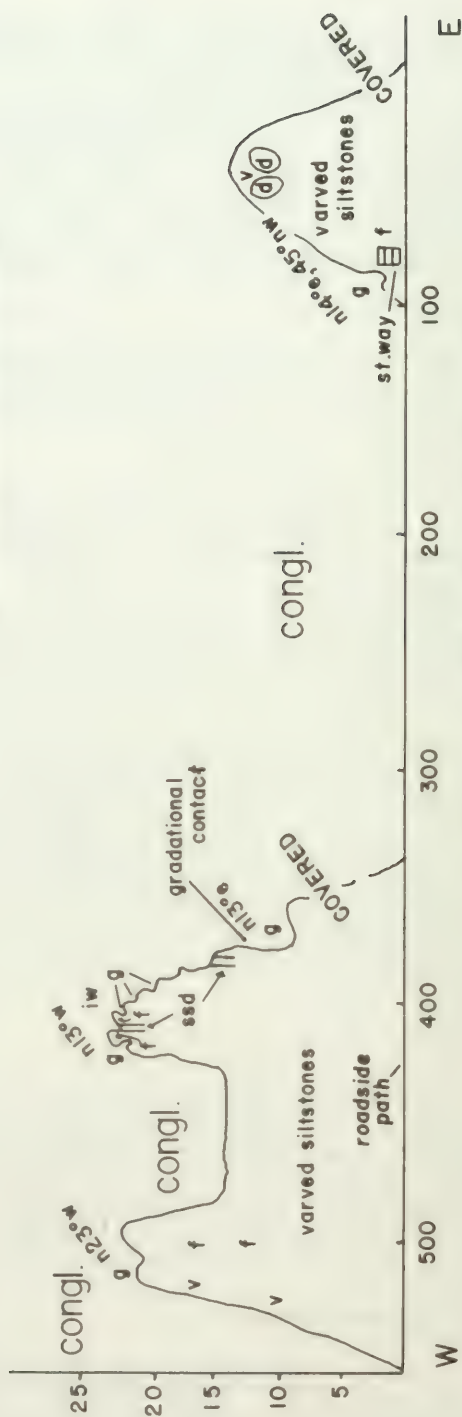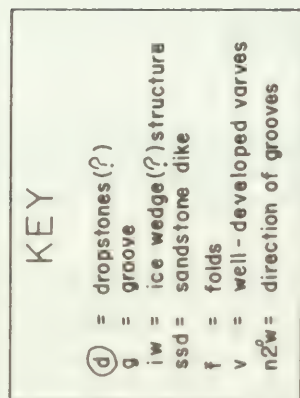
Control = pace and compass in feet
Vert. Exag. = 5.6x

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tion and contorted bedding forms in proglacial lake delta deposits (Koteff and Stone, 1971). Such folds are present in the siltstones at the Beacon Street outcrop (Stop #1). They are best developed at the western end (Fig. 2) where several are recumbent and some are truncated, apparently by penecontemporaneous erosion. Other folds, possibly slump blocks, and small faults are present in the siltstone outcrop on the lower campus of Boston College (Stop #2). Skehan (1975) attributed these deformation structures to slumping while the sediments were still soft.

Clastic Dikes:

Two clastic dikes of light brown friable sandstone occur in the top of the siltstone at the Beacon Street outcrop (Stop #1). Although the sand may have filled in these cracks from above, possibly those of ice wedges (see above), the sand may have also been injected from below. Fairbridge (1974, p. 325) reported small-scale features on ancient proglacial sand plains, such as sand volcanoes formed as "...spring deposits that are commonly caused by a heavy load forcing the subsurface melting ice-water (with sand) up through cylindrically bored escape channels marginal to the area that is loaded." Such features may be subaqueous or subaerial.

The poorly preserved tree trunk-like casts from the Roxbury Conglomerate reported by Burr and Burke (1900) might also be clastic dikes, i. e., not of organic origin. Similar features have been reported from rocks elsewhere (see Shrock, 1948), such as the Late Cambrian Potsdam Sandstone of Ontario and New York (Cushing and others, 1910; Hawley and Hart, 1934). The resemblance of the latter to tree trunks has been noted but never taken seriously! The origin of these structures has been attributed to seismic shocks which can form sand vents and craterlets (Shrock, 1948). The November, 1755, earthquake in the Boston area, for example, was so severe in Scituate that, "In swampy ground waterspouts burst out and a spring was started which is still flowing" (Crosby, 1928, p. 96).

Summary:

In environmental stratigraphy, as in many fields of geology, multiple lines of evidence must often be sought in order to solve difficult and ambiguous problems about the nature of ancient depositional environments. Because of the use of inductive and inferential reasoning, we may never be able to prove the truth of our assertions in many cases (Laporte, 1968). In this study of the effect of glaciation on the deposition of the Brookline Member of the Roxbury Conglomerate, we have described the occurrence of six sedimentary features, i. e., dropstones, varve-like bedding, grooves, ice wedging-like structures, contorted beds, and clastic dikes. Although each of these features can be attributed to a different non-glacial origin, the factor that they have in common is a possible glacial and/or proglacial origin which we favor.

DISCUSSION

As pointed out above, we believe the uniqueness of a North American Paleo-zoic glaciation in the Boston Basin makes a late Paleozoic age untenable. Although a mid-Paleozoic age is now favored by many workers, paleoclimatic correlation with the Late Ordovician-Early Silurian glaciation in northwest Africa (Lenz, 1976) seems more acceptable to us (Fig. 3). There is no definite sedimentary or paleon-tologic evidence from the Boston Basin to refute a Late Ordovician or Early Silurian age. Some unavoidably unreliable dates of the basinal volcanics allow for an

Figure 3

EARLY PALEOZOIC GLACIATIONS AND PLATE TECTONIC
POSITIONS OF BOSTON AND NORTHWEST AFRICA
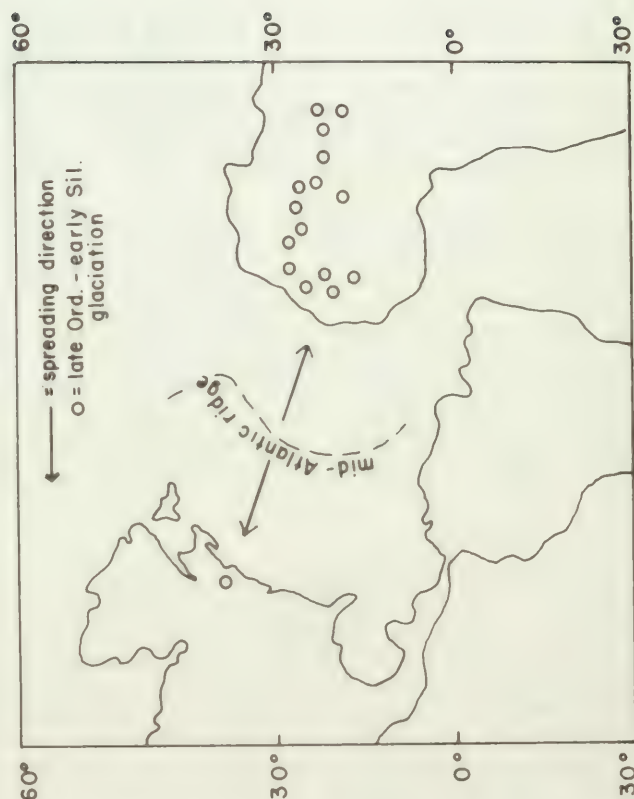
(map modified from Heirtz,1968, glacial data from Fairbridge,1970)

Ordovician age (Fairbairn and others, 1966). A Late Ordovician age may be a lower limit, however, because radiometric dates of the surrounding granitic terrane indicates Late Silurian to Late Ordovician dates (400-450 m. y.) (Zartman and Marvin, 1971; Lyons and Krueger, 1976; Naylor and Sayer, 1976).

It is clear that there was a proto-Atlantic ocean of considerable dimensions during the Ordovician that separated North America from Africa (Wilson, 1966; Dewey and Bird, 1970; McElhinney and Opdyke, 1973). In addition, North America was located at low latitudes during the Ordovician (McElhinney and Opdyke, 1973) while northwest Africa was located in the region of the southern (Gondwana) pole (Fairbridge, 1970, 1974; McElhinney and Opdyke, 1973). However, as pointed out by Wilson (1966), the Boston area contains a Cambrian Acado-Baltic (Atlantic) fauna, e. g., in the Braintree Argillite, which is more akin to European and African than American Cambrian faunas in the western Appalachians. Other such anomalous Cambrian faunas are located in maritime Canada. These can be explained if the North American, European, and African continents converged in Late Paleozoic time and did not split along the same exact zone when the continents broke up again during the early to medial Mesozoic. The suture zone or zones would therefore be somewhere west of the Boston area.

Thus, based on faunal evidence, the Boston area represents, in the opinion of some geologists, a remnant of proto-Africa. This is supported by the evidence for glaciation during the deposition of the sedimentary rocks of the Boston Basin. The source of the coarse clastics for the Boston Basin is to the south and the supposed glaciers must have moved northward. Those of the northern African Sahara during Late Ordovician time also moved northward with respect to our present poles.

PALEOGEOGRAPHIC RECONSTRUCTION

Glaciers must have covered a region of some extent and relief to the south, and an intermontane lake probably existed to the north that must have been fed by glacial melt-waters. Occasionally, the glaciers, possibly alpine in nature, extended down to the lake margin, e. g., evidence described herein for glacial activity in the lower Brookline Member. During ablation when glaciation was extensive, till was deposited in the basin, such as at Squantum. Normally, however, most of the till was deposited some distance to the south and reworked by melt-water streams on an outwash plain that extended northward to the lake margin, forming the thick conglomerate-sandstone sequence of the Brookline Member. In the proglacial environment, permafrost conditions must have prevailed from time to time, as indicated by such features as ice wedging.

To the north, varves and possibly turbidites were deposited in a lake basin with some of the fine-grained sediments along the lake margin slumping downslope into deeper waters. Occasionally, ice rafted stones from icebergs were dropped into the lake bottom sediments. As the glaciers advanced and receded the lake shores must have also varied. The more argillaceous Dorchester Member and the upper Cambridge Argillite suggest a southern shoreline that transgressed significantly southward at least two times.

The Brookline Member may represent a progradational situation due to significant glacial activity to the south. The overlapping southward of the upper Cambridge Argillite over the Brookline Member suggests diminution of glacial activity after a time and perhaps lower relief southward than assumed by many geologists.

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Mileage Log

This mileage log is designed to start at Boston University. Mileage was taken from a car's odometer and the hundredths of a mile are estimated, especially where turns occur in rapid succession. The outcrop stops of this field trip are in the USGS Newton 7 1/2 minute topographic guadrangle map (1956).

*CuMi   *InMi

0.00   0.00   Start at corner of Granby Street and Commonwealth Avenue (Boston University Stone Science Building at NW corner of intersection; Boston University Warren Towers dormitories are across the street at #700 Commonwealth Avenue). Head west (outbound) on Commonwealth Avenue.

1.1   1.1   "Y" intersection with Brighton Avenue. Bear left and stay on Commonwealth Avenue.

*   CuMi = Cumulative Mileage; InMi = Incremental Mileage.

CuMi	InMi
3.05	1.95	Turn left onto Chestnut Hill Avenue. (You can now follow the course of this trip with the locality map on the next page.)
3.25	0.2	Cleveland Circle; turn right onto Beacon Street.
3.4	0.15	Chestnut Hill Reservoir works on right and ball playing field on left. Continue on Beacon Street which follows the periphery of the reservoir.
4.2	0.8	Boston College on right. Stop 2 of this field trip is the outcrop behind the baseball backstop to your right. Stay on Beacon Street and pass Boston College area.
5.0	0.8	Intersection with Hobart Road on right (becomes Hammond Pond Parkway to the left). Continue through intersection.
5.1	0.1	Park on roadside on the right next to the beginning of the outcrop.

Stop #1 Outcrop of siltstone and conglomerate facies of Brookline member of Roxbury Conglomerate for about 700 feet along the roadside from where you parked westward to where Beacon Street and Bishopsgate Road Intersect.

Two masses of siltstone occur beneath conglomerate that is continuous across the middle and top of this outcrop (Fig. 2). Because the conglomerate at this outcrop will be described in detail by others in this guidebook, we shall confine our discussion mostly to the siltstone facies and its contact with the overlying conglomerate. The contact has been considered in the past either an unconformity or a thrust fault. Although the siltstone laminations are often truncated by erosion, they grade upward in places into sandstone and conglomerate. The irregular contact could have been caused by fluvial channeling or glacial scouring. Grooves that resemble glacial grooves are visible at several locations (Fig. 2), but these could also have been caused by channeling, especially the easternmost groove.

Throughout this outcrop, the undisturbed siltstone laminations approach, to varying degrees, varve-like couplets suggestive of glaciolacustrine sedimentation although they may be turbidites. In addition, occasionally there are small-scale cross-laminations and small to large-scale slump-like and/or fold structures.

In the easternmost siltstone mass there are two large clasts, a pebble and a cobble (Fig. 1). These occur in the same horizon near the top (Fig. 2), rest on depressed laminations, and have the upper laminations draped over them. They are interpreted to be dropstones, possibly ice rafted.

Figure 4

LOCALITY MAP

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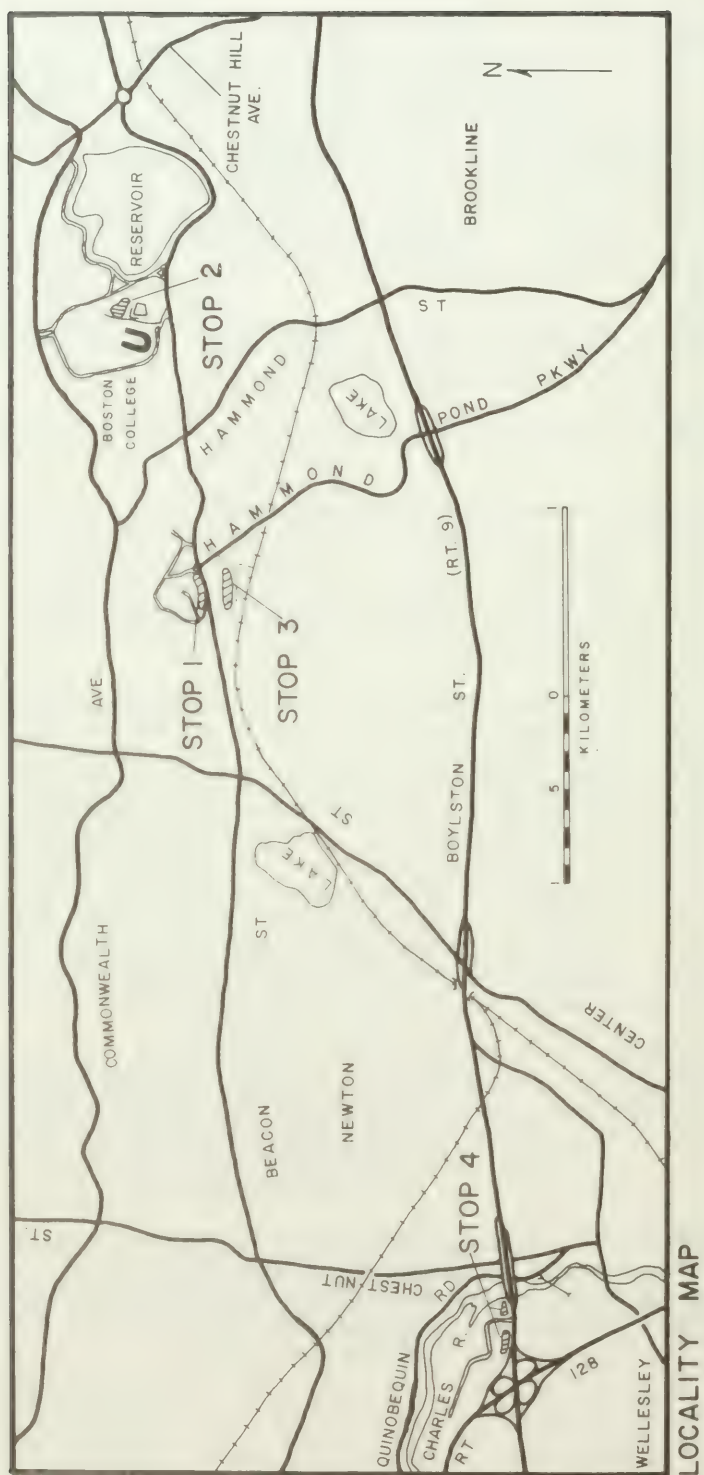
The top of the eastern part of the western siltstone mass
contains two clastic dikes. The eastern one is filled with
friable sandstone. The western one also contains friable
sandstone, but its widening top is filled with conglomerate.
This wedge-shaped crack has contorted siltstone laminations
on either side with some on the western side faulted. It is
interpreted as a possible ice wedging structure.

Folds in the siltstone are especially well-developed at the
western end of the outcrop. They could be folds due to slumping
(possibly in a glacial lake), drag folds, or folds formed by the
pressure of overriding glacial ice. Some of the small contorted
horizons near the westernmost stone stairway on Bishopsgate Road
are truncated, apparently by penecontemporaneous erosion.

CuMi	InMi	
5.1	0.00	Return to car. Make a "U"-turn on Beacon Street (watch carefully for fast moving traffic) and head east.
5.2	0.1	Intersection with Hammond Pond Parkway. Continue east on Beacon Street until you are in the Boston College area and can see the Chestnut Hill Reservoir again.
6.1	0.9	Turn left into Boston College parking lot entrance.
6.12	0.02	Turn right into parking lot, driving down hill, bear right and drive along the side of the playing field.
6.2	0.08	When you reach the baseball backstop area (tall metal chain link fence behind home plate) park. (If you are using the 1956 Newton 7 1/2 min. quadrangle map, note that the two western ponds of the Chestnut Hill Reservoir have been filled in and are now part of the Boston College Lower Campus.)

Stop #2: Walk over to the wooded hillside due east from the
northeast corner of the football stadium where two outcrops
of siltstone occur on the hillside. The larger one to the
left is behind the small metal (chain-link) fenced-in area.
Its western third contains slump folds and possibly slump
blocks (Skehan, 1975, Stop 8). These may be due to soft
sediment deformation soon after deposition which is common in
glacial lake deposits. However, there are some minor faults
with 1-2 inch displacements, and these rocks are slightly
metamorphosed - low grade as indicated by epidote and chlorite
along some bedding and joint surfaces. Mansfield (1906), LaForge
(1932), and Bell (1948) interpreted an east-west trending fault
through here, but Skehan (1975, P. 18-21) notes a north-south
fault about 1,000 feet west at the steep slope on the other
side of the stadium.

The siltstone is cleaved (Skehan, 1975), grayish pink,
laminated, and contains discontinuous sandstone horizons. There

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are no conglomerate beds, but 5 isolated pebbles (Fig. 1) occur in the middle of the larger siltstone outcrop (Skehan, 1975, p. 18). Four are in a single layer while a fifth is in a layer 12 inches below them. The siltstone laminations beneath them are depressed downward and those above drape over them. We interpret them to be dropstones, possibly ice rafted.

CuMi	InMI	
6.2	0.00	Return to car, drive through parking lot, and return to Beacon Street.
6.35	0.15	Turn right on Beacon Street.
6.7	0.35	Intersection with Hammond Street. Go straight.
7.15	0.45	Turn left at intersection with Hammond Pond Parkway (becomes Hobart Road to the right).
7.25	0.1	Park on grass shoulder to the right just beyond 4th utility pole south of Beacon Street.

Stop #3: Newton Webster Conservation Area (refer to Rehmer & Roy, this volume, Fig. 3, for a geologic map and trail for this area.) Beware of POISON IVY! Walk to the beginning of the unmarked, dirt trail about 15 feet south of the utility pole and head southwest on the trail for about 225 feet until it branches to the right (Fig. 4) by the beginning of the east-west trending outcrop. (If you cross a small stream, you have gone approximately 125 feet too far.)

Proceed about 340 feet in a westerly direction along the path until it jogs right for about 10 feet and then continues westerly again. At this point, there is an exposure of the Brighton Volcanics on the right. (It is massive except at its top, exposed about 100 feet west, where it is amygdaloidal.) After about another 160 feet westward, a north-south metal, chain-link fence will be encountered. Go through the opening to the right and continue west for about 235 feet to a small clearing beneath a cliff on the right (North). (Be careful of the steep cliff with about a 20 foot drop on the left.)

At this location the basaltic volcanic horizon is overlain by slightly purplish maroon sandstone which is, in turn, overlain by conglomerate. The top of the basalt is amygdaloidal and contains sandstone fragments, while the base of the sandstone contains basaltic fragments (clinkers?). The sediment above the volcanic horizon varies from shale (fissile) to fine-grained sandstone to coarse-grained and pebbly sandstone. Ripple marks are occasionally present in the sandstone which is up to 18 feet thick.

To the west, under the large overhanging ledge, pebbly sand-
stone grades eastward, over a distance of about 10 feet, into
horizontally laminated sandstone with many pebbles "floating" in
the finer sandy matrix. Good examples of dropstone-like pebbles
can be seen about one foot above the ground immediately beneath
the right side of the overhang. Being that these isolated pebbles
are in a sandstone, rather than in a varved(?) siltstone, we
hesitate to interpret them as ice-rafted dropstones. They could
have been deposited by a water current at the transition between
the low and high flow regimes.

CuMi	InMi	
		Return to car by walking back along the trail to Hammond Pond Pkwy.
7.25	0.00	Proceed (carefully south again on Hammond Pond Parkway. Scattered outcrops of the Brookline Member of the Roxbury Conglomerate will be seen along this road for the next mile.
7.95	0.7	A sandy facies of the Brookline Member is on the inside of this curve in the road and a basaltic intrusive occurs on the outside of the curve (rear stop 9C of Skehan, 1975).
8.1	0.15	Bear right and take access road to Route 9 west.
8.25	0.15	Enter (carefully) Route 9 (also called Boylston Street) going west.
8.50	0.25	Roxbury Conglomerate on right.
8.75	0.25	Roxbury Conglomerate on right.
9.0	0.25	Roxbury Conglomerate on left.
9.2	0.2	Take underpass.
9.8	0.6	Take overpass.
10.6	0.8	Basalt on left.
10.75	0.15	Don't take overpass, but bear slightly to the right and take service road (parallel to Route 9) downhill.
10.95	0.2	Go straight ahead at intersection with Chestnut Street.
11.0	0.05	Go straight ahead at intersection with Quinobequin Road and drive slowly up the access road to Route 9, keeping to the right.
11.05	0.05	Crossing over the Charles River.
11.1	0.05	Park as far to the right as possible just before the outcrop.

Stop #4: This outcrop (briefly reviewed by Skehan, 1975, Stop 22E)
is divided into two parts: the first is on the north side of Route
9 between the Charles River and William Street, the second is along
the northbound ramp of Route 128 from Route 9W. The first area

contains northward dipping conglomerate cut by a vertical basaltic dike (with xenoliths). The dike-conglomerate contact is offset to the west by a fault which can be seen on top of the hill above the road cut. Low grade metamorphism, probably associated with the faulting, is indicated by the chrysotile and chlorite present in veins and along slickensided surfaces in the basalt.

The second part of this stop, west of William Street, does not exhibit the intensity of metamorphism that is found east of William Street. The sequence here starts with soft, essentially uncemented, purplish, fissile, siltstone (1 to 2 feet thick) with varve-like banding. It is overlain by well-indurated, horizontal and cross-laminated, pebbly, arkosic sandstone (1-1/2 to 12 feet visible). The sandstone, in turn, generally grades upwards, although there is an abrupt contact in places, into a pebble conglomerate about 35 feet thick which becomes a pebbly cobble conglomerate at the top of the section.

The soft siltstone (N80W, 55N) was augered to a depth of 5 feet parallel to bedding 2-1/2 inches below the hard sandstone without becoming noticeably harder. This will be demonstrated on the field trip. We cannot explain why this silt is so unconsolidated. Even if the Boston Basin were late Paleozoic in age, as believed by many geologists, we still could not explain why this siltstone is so unconsolidated in comparison to all of the other siltstones visited on this trip. Although varve-like bedding is present in the siltstone, dropstones have not been found here.

CuMi   InMi

Return to car.

11.i   0.00   Proceed (carefully) onto Route 9 going west, as you cannot make a U-turn on Route 9 in this vicinity in order to return to Boston.

11.45   0.35   Bear right and get onto the Route 128 southbound ramp.

11.6   0.15   Go onto Route 128 from ramp, but keep to the right.

11.7   0.1   Take exit #55E. (#52 on 1956 USGS Newton 7 1/2 minute Quadrangle Map).

11.9   0.2   Go onto Route 9 eastbound from ramp. (You have to go this way.) You are now heading east and back to Boston.

16.7   4.8   Turn left onto Chestnut Hill Avenue.

17.45   0.75   Intersection with Beacon Street. If you take a right, it will take you to Kenmore Square and downtown Boston.

17.7   0.25   Turn right onto Commonwealth Ave. and continue on Commonwealth Ave. to reach Boston University, Kenmore Square, and downtown Boston.

THE BLUE HILLS IGNEOUS COMPLEX

BOSTON AREA, MASSACHUSETTS

by

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The essential rock units of the Blue Hills Igneous Complex are the
following:
  (1) Aporhyolite (felsic volcanics, partially devitrified),
  (2) Blue Hills Porphyry (microperthite, quartz porphyry with varying
                     amounts of fine-grained matrix),
  (3) Quincy Granite (microperthite, quartz, hornblende, aegirite, medium-
                     to coarse-grained, peralkaline, holocrystalline granite).
The Aporhyolite and the Blue Hills Porphyry are well exposed in the Blue Hills
highlands, whereas the Quincy Granite underlies the lowlands immediately to
the north. To the north of the Blue Hills lies the (Upper Devonian (?))
Boston Basin and to the south lie the (Carboniferous) Norfolk and Narragansett
Basins.

Our work, and hence this field-trip, is concerned chiefly with the units
discussed above. An earlier N.E.I.G.C. Trip (Chute, 1964) provides a broader
sampling of the units exposed in the area. The units are mapped and described
by Chute (1966 and 1969), the latter reference being a $7\frac{1}{2}$-minute geologic map
of the trip area. Although we do not disagree with the correlation, we pre-
fer to retain the earlier name, "Aporhyolite," for the felsic volcanics of the
Blue Hills area rather than lumping them with the Mattapan Volcanics as Chute
did. Also, we prefer the usage "Blue Hills Porphyry" to Chute's "Blue Hills
Granite Porphyry."

Like so many units in the Boston area, the Blue Hills units have proved
very hard to date. Three recent papers (Bottino and others, 1970; Zartman and
Marvin, 1971; and Lyons and Kreuger, 1976) discuss isotopic ages for these
rocks. As we will see, the age-patterns are complex and even after consider-
able interpretation cannot be wholly reconciled with the field data. We are
concerned that heretofore there has been insufficient interaction between the
field and isotopic data. Chute's publications are based on fieldwork substan-
tially completed in the thirties; he had access only to the preliminary
isotopic results of Bottino (1963) and of Zartman (written communication).
The mission of Sayer's thesis (Sayer, 1974) under Naylor's supervision was
to re-examine the critical field relationships in light of the isotopic data.
In so doing, we have found it profitable to focus on the Blue Hills Porphyry.

THE PORPHYRY PROBLEM

Earlier workers in the Blue Hills area (Warren, 1913; Chute, 1940) believed that the Blue Hills Porphyry was a chilled border phase of the Quincy Granite and that the Aporhyolite was an extrusive expression of the same series of magmas. Our study supports this conclusion.

The possibility exists, however, that the Blue Hills Porphyry might be a significantly younger unit. Taken at face value, the Rb-Sr data of Bottino and others (1970) suggest an age of 280 million years (m.y.) for the Blue Hills Porphyry, whereas all the isotopic data suggest the Quincy Granite is considerably older. Noting the apparent conflict with the field relationships, the geochronologists have mostly concluded that the Porphyry has been disturbed -- that its apparent isotopic age probably does not reflect the true age of intrusion. It is interesting to note, however, that several of the field geologists concerned with the problem have taken the opposite stance. Influenced by the isotopic results, Chute (1969) pointed out that the field relationships do not provide conclusive data for determining the age of the Blue Hills Porphyry relative to the Quincy Granite, and reversed his earlier conclusion that the Porphyry was the older of the two units. In a similar vein, D.R. Wones and D.K. Riley (1971, personal communication) suggested to us that at least part of the Blue Hills Porphyry might be of Carboniferous age. They were influenced partly by the Rb-Sr data (the isochron for the Porphyry is remarkably straight for a disturbed system) and partly by their interpretation of the contact relationships of the Porphyry with the Carboniferous Pondville Conglomerate as seen at the large roadcut at the intersection of Routes 28 and 128 (STOP 7). Some features of this roadcut, constructed after the completion of most of Chute's fieldwork, can be interpreted to suggest that the porphyry grades into the Pondville Conglomerate. This would suggest a Carboniferous age for the Porphyry, compatible with the 280 m.y. isochron.

One of the earliest results of Sayer's field work was to show the lack of any lithologic basis for separating a Carboniferous porphyry unit from the main body of the Blue Hills Porphyry. Although the unit is highly variable in character, there are no consistant areal differences and the entire unit appears to be of the same age. Warren (1913) had noted that the Blue Hills Porphyry and the Quincy Granite are closely similar in their major-element chemistry and in their mineralogy. Both are alkaline or peralkaline in chemistry and both contain distinctive minerals like riebeckite and astrophyllite. Sayer (1974) analyzed the Blue Hills Porphyry for trace-elements and showed that it has the same distinctive trace-element distribution patterns as the Quincy Granite (Buma, Frey, and Wones, 1971). The close similarity of the Blue Hills Porphyry and the Quincy Granite in so many distinctive features strongly suggests that they are co-magmatic and hence should be similar in age.

To resolve this controversy it would be helpful if one could prove the earlier contention that the Blue Hills Porphyry pre-dates the Quincy Granite. We have been unable to prove this, and agree with Chute (1969) that the contact relationships are inconclusive on this point. Several of the lines of evidence are discussed in the descriptions of STOP 2 and STOP 4 of this trip. We can only say that there is a considerable body of evidence suggesting that

the Blue Hills Porphyry and the Quincy Granite are consanguinous, and that, except for the Rb-Sr isotopic data, we can find no evidence to the contrary.

THE AGE PROBLEM

Because we conclude that the Blue Hills Porphyry and the Quincy Granite are comagmatic and of about the same age, we must explain the apparent conflict between this conclusion and the isotopic age results.

Bottino and others (1970) determined a sixteen point Rb-Sr whole-rock isochron with an age of 282 ± 8 m.y. and an initial Sr^{87}/Sr^{86} ratio of 0.717 for the Blue Hills Porphyry and a six point isochron with an age of 365 ± 7 m.y. with an initial Sr^{87}/Sr^{86} ratio of 0.703 for the Quincy Granite. Zartman and Marvin (1971) determined an eight point Rb-Sr whole-rock isochron with an age of 313 ± 22 m.y. and an initial Sr^{87}/Sr^{86} ratio of 0.731 for the Quincy Granite, with two points for the Blue Hills Porphyry lying on the same line. Each of the isochrons shows some scatter of the data and, because of generally high Rb/Sr ratios owing to the alkalic character of the rocks, the initial Sr^{87}/Sr^{86} ratios are not well defined. As an exercise we tried combining and "cleaning" these data. "Cleaning" involved removing several samples collected near alteration zones, several samples with poor analytical reproducibility, and several samples whose locations are uncertain. Some of Bottino's data were measured on samples previously collected by Billings for petrographic work rather than for age determination, and these samples were also dropped in the "cleaning" process. Our result was a thirteen point Quincy Granite isochron with an age of 319 m.y. and an initial Sr^{87}/Sr^{86} ratio of 0.725, and an eight point Blue Hills Porphyry isochron with an age of 281 m.y. and an initial Sr^{87}/Sr^{86} ratio of 0.722 ($\lambda Rb^{87} = 1.39 \times 10^{-1}$ yr^{-1}).

Zartman and Marvin (1971) reported K-Ar ages of 430 to 458 m.y. on six samples of riebeckite from the Quincy Granite and 301 m.y. on one sample of riebeckite from the Blue Hills Porphyry. They also dated one sample of zircon from the Quincy Granite with the following results: Pb^{207}/Pb^{206} age 437 ± 32 m.y.; Pb^{207}/U^{235} age 416 ± 15 m.y.; and Pb^{206}/U^{238} age 413 ± 8 m.y. We attempted to date the Blue Hills Porphyry but failed to obtain sufficient zircon from an 80 kg sample for an analysis.

We interpret these data to conclude that an age of approximately 420 m.y. (Late? Silurian) gives the best estimate of the time of intrusion of the Quincy Granite and the Blue Hills Porphyry. This is close to the lead/uranium ages of the Quincy Granite zircon sample. The Pb^{207}/Pb^{206} age of 437 is a reasonable upper limit for the time of emplacement but it may appear slightly too old owing to inherited radiogenic lead. Radon (intermediate daughter) loss could lower the Pb^{206}/U^{238} age, but the pattern of discordance does not suggest this effect has been important. The Pb/U ages are sensitive to later disturbances, but the low metamorphic grade of the rocks suggests this effect is slight. Because riebeckite contains little potassium, inheritance of small amounts of radiogenic argon could make the riebeckite K-Ar ages appear slightly too old.

How then do we explain away the Rb-Sr results. If the Blue Hills Porphyry and the Quincy Granite are comagmatic, both isochrons cannot be correct, and our conclusion is that neither is correct. Despite the fact that the "cleaned"

isochrons are relatively straight (show relatively little scatter) we con-
clude that both isochrons are profoundly disturbed and suggest the following
explanation. It is well-known that Rb-Sr mineral ages are easily disturbed
and that radiogenic Sr^{87} readily migrates from Rb-rich minerals during very
slight disturbances. Normal granites appear to behave as closed systems
during such disturbances only because they contain minerals like plagioclase,
apatite, and epidote that take up the labile Sr^{87} before it can leave the rock
system. The alkalic Quincy Granite and Blue Hills Porphyry are notably
lacking in such Sr-acceptor phases, hence it seems quite likely that radio-
genic Sr^{87} could migrate entirely out of these rocks during even slight dis-
turbances (and possibly may even continuously diffuse out of these rocks).
If radiogenic Sr^{87} is not reabsorbed by the rock, it could be lost in direct
proportion to the Rb-content of the rocks (the factor governing the place and
rate at which radiogenic Sr^{87} is produced) hence, even though highly disturbed,
the isochrons could appear straight and show little scatter.

NATURE OF THE IGNEOUS COMPLEX

    Kaktins (1976) has shown that the Aporhyolite can be subdivided internally
into a number of stratigraphic units, many of which appear to be of ignim-
britic, ash-flow origin.

    The Blue Hills Porphyry and the Quincy Granite are probably plutonic
expressions of the same magmas that produced the Aporhyolite. These magmas
appear to have been rather hotter and drier (see Buma, Frey, and Wones, 1971)
than normal for granitic rocks, and they appear to have been emplaced at
relatively shallow depths. Note that the plutonic rocks crystallized above
the feldspar solvus to produce one-feldspar rocks. Aplite veins and pegmatites
are rare, suggesting a hot, dry magma, although the Quincy Granite probably
approached saturation with water in the latest stages of crystallization. The
Quincy Granite (Buma, Frey, and Wones, 1971) and the Blue Hills Porphyry
(Sayer, 1974) show considerably less depletion of the heavy rare-earth elements
than is typical for granites. Such depletion is one of several indices of
overall differentiation, hence these magmas appear relatively primitive com-
pared to other New England granites. We believe it is possible that the Blue
Hills magmas are mantle-derived and have interacted only slightly with crustal
materials.

REGIONAL RELATIONSHIPS

    The Blue Hills Igneous Complex is probably part of a major belt of Late
Silurian and Early Devonian volcanic and intrusive rocks along the southeastern
margin of the Northern Appalachian Mountains. Gates (1969) has shown that the
volcanic rocks of this belt include the Lynn Volcanics (Boston North Shore),
the Newbury Volcanics, and the Pembroke, Edmunds, Eastport, and other volcanic
units exposed on the east coast of Maine from Penobscot Bay to Eastport. We
consider the Aporhyolite to be a volcanic member of this same belt.

    As in the Blue Hills, the following alkaline, hypersolvus granites are
probably closely related to the same general episode of igneous activity: the
Peabody and Cape Ann Granites (Boston North Shore); Cadillac Mountain, Tunk
Lake and related granites in the Bar Harbor area, coastal Maine; Red Beach and
St. George Granites (Passamaquoddy Bay area, Maine and New Brunswick);and
possibly the St. Lawrence and related granites in southeastern Newfoundland.

We would suggest that Rb-Sr dates on these granites (see Metzger, 1975; and Bell, 1974) may be subject to the same interpretive problems as encountered in the Blue Hills area. In terms of plate-tectonic reconstructions, this belt may indicate the presence of a major subduction zone in Late Silurian through Early Devonian time.

Chute (1969) correlated the Aporhyolite with the Mattapan Volcanics underlying the Boston Basin. While we prefer to retain the older name, Aporhyolite, for the volcanics of the Blue Hills area, we do not disagree with this correlation. Most, if not all, of the Mattapan Volcanics are probably of Late Silurian to Early Devonian age and are probably part of the volcanic belt discussed above. Why then have the Mattapan Volcanics commonly been assigned a younger age? The Brighton Volcanics interfinger with the sedimentary rocks of the Boston Basin, which are probably Upper Devonian or younger. Many previous workers (see for example, Billings, 1929) have inferred a gradational contact between the Brighton Volcanics and the underlying Mattapan Volcanics, and have used this relationship to "pull up" the inferred age of the Mattapan Volcanics. From the regional relationships we believe it is more likely that the Mattapan Volcanics lie unconformably beneath the Brighton Volcanics and the other units of the Boston Basin, and that there is no compelling reason to assign an age younger than Late Silurian or Early Devonian to the Mattapan Volcanics.

Finally, we would like to stress the relatively unmetamorphosed condition of the Siluro-Devonian (and even of the Late Precambrian) volcanic and igneous rocks along the east coast of New England and Maritime Canada. This places strict limits on the intensity of Acadian and post-Acadian metamorphism throughout much of this belt, although only a short distance to the northwest very intense Acadian metamorphism is widespread. As D.B. Stewart has so succinctly observed, there appears to be very little Acadian disturbance in Acadia itself. We believe that failure to appreciate this observation has prejudiced many previous attempts to date units along the southeastern margin of the Appalachians. The observation also raises the question as to whether this belt was as close to the Appalachian mainland in Siluro-Devonian time as it is today.

We conclude with some remarks on the dating of the Boston Basin units, for which we believe the most probable age is Late (?) Devonian. Most previous workers have correlated the Boston Basin with the nearby Norfolk and Narragansett Basins of Carboniferous age, but we can find no compelling reasons for doing so. We note similarities between the units of the Boston Basin and those of the Perry Basin (Eastport area, Maine) dated as Upper Devonian by plant fossils. Not far from the Perry Basin are clastic, red-bed units ranging in age from Mississippian through Triassic with which the Perry Basin no doubt would have been correlated had it not yielded Upper Devonian fossils. We know of no fossil evidence from the Boston Basin to contradict an age as old as Upper Devonian. It has long been appreciated that the Roxbury Conglomerate at the base of the Boston Basin sequence contains abundant clasts of felsic volcanics resembling those of the Mattapan Volcanics and the Aporhyolite. The Roxbury, however, lacks clasts of the deeper-seated Blue Hills Porphyry and Quincy Granite, whereas clasts of the Blue Hills Porphyry are abundant in the Norfolk Basin deposits. These observations could be explained simply by unroofing to progressively deeper levels if the Roxbury Conglomerate were regarded as pre-Carboniferous.

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Sketch map to accompany STOP 4

PLANETABLE MAP
SUMMIT AREA
CHICKATAWBUT
HILL
QUINCY, MA

BLUE HILLS
PORPHYRY

BLDGS

?

x
x

x

x

x

x x
x x x
x x x
x x

FENCE ─x─x─┐ ┌─x─

QUINCY ?
GRANITE

x

x

M. LOISELLE
S. SAYER
AUG 1974

50   0   50
                              FEET

SCALE

141
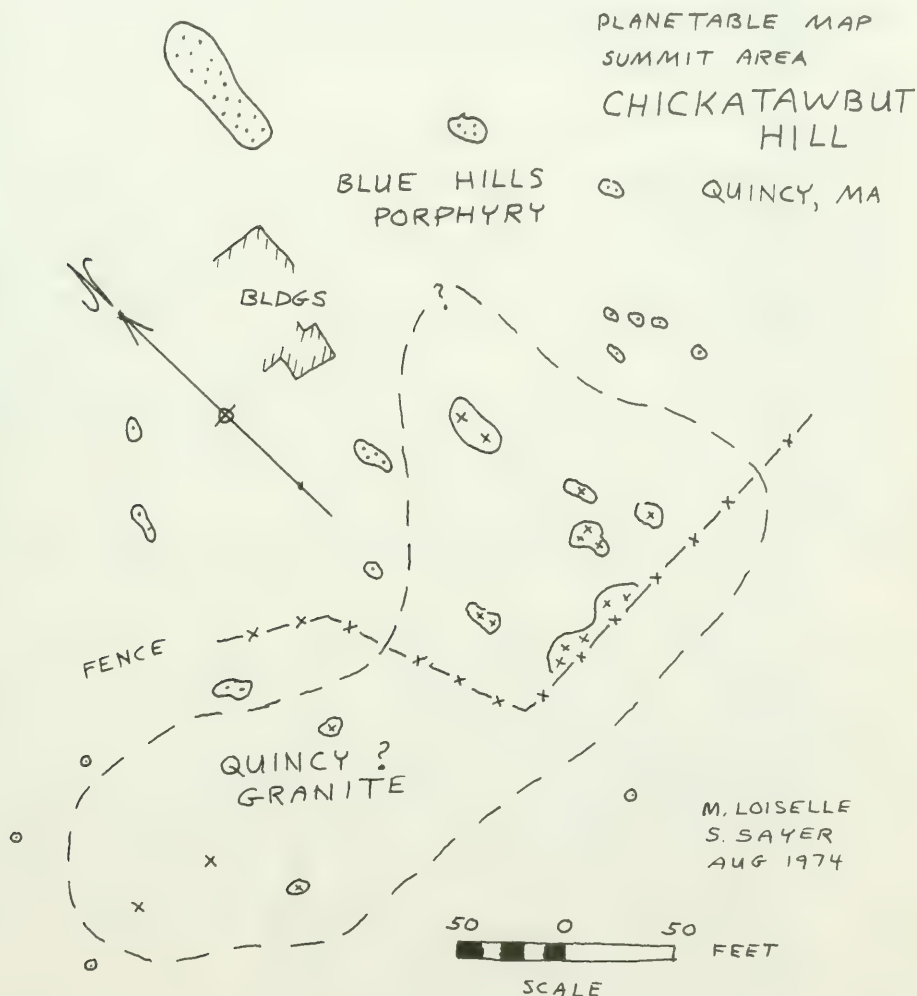
MILES

Mileage count for this trip begins on leaving STOP 1. To reach STOP 1
from BOSTON UNIVERSITY proceed eastward on Commonwealth Ave to Mass-
achusetts Ave; RIGHT (don't drop into underpass) onto Massachusetts
Ave, thence south about 1½ miles to SOUTHEAST EXPRESSWAY SOUTHBOUND.
(Massachusetts Ave passes under hospital and there may be construction
detours; follow signs to Expressway.) Leave Expressway at EXIT 24,
noting "Mr. Tux" Store on your right. This is your destination, but
you are not allowed to backtrack on Willard St. to get there directly.
Merge onto Willard St southbound then turn LEFT at interchange, passing
under Expressway then back north following signs for Willard St. Turn
LEFT onto Willard St (don't get back on Expressway), thence back
under Expressway to "Mr. Tux." Entrance to Quincy Dump on right. If
gate is closed make U-turn and park here; if gate is open you can drive
½ mile closer to the outcrop.

0.0   STOP 1   QUINCY GRANITE QUARRIES

Proceed about ½ mile past gate to telephone pole #10 at the top of the
hill. South of the road (left) are piles of Braintree Argillite exca-
vated from the Fore River Shipyard. We will see Braintree in place
at STOP 6, but here is the better place to look for fossils. Trails
to north (right) lead to the quarries. CAUTION: WATCH FOR SHEER DROPS!
(This is a popular rock-climbing locality. Don't make an unanticipated
first-descent without proper equipment. Don't leave children unattended.)

On the official trip we will stay here exactly ONE HOUR. This is the
sort of place where everyone gets spread out. Note time when you leave
the vehicles and keep track so you don't get left.

The QUINCY GRANITE is a grey, medium- to coarse-grained, holocrystalline
rock. The major minerals are microperthite, quartz, hornblende, and
aegirite. Minor minerals include fluorite, zircon, riebeckite, mag-
netite, aenigmatite, astrophyllite, sphene, hematite, parisite,
synchisite, siderite, and calcite. The molar ratio $Na_2O + K_2O/Al_2O_3$
is slightly greater than unity, hence the Quincy is designated as a
peralkaline granite. The Quincy may be compared with the Peabody and
Cape Ann Granites of the north shore; the Quincy is slightly more
alkaline, slightly more oxidized, and slightly wetter (Buma, Frey, and
Wones, 1971). Its hot, dry character (this is a hypersolvus, one-
feldspar granite) and its relatively undifferentiated rare-earth
distribution pattern suggest the Quincy Granite may be mantle-derived.
While in the quarries note the massive character of the granite and
search for xenoliths, aplite veins, pegmatites, and similar features.

0.0   Quincy Dump Gate at Mr. Tux Store (re-set mileage if you drove into the
        quarries); turn RIGHT onto Willard St.
0.2   bear RIGHT following Willard St.
0.3   bear RIGHT onto Wampatuck Road (not named on signs) following MDC signs.
0.7   Babel Rock (diabase plug) on right at curve

1.0   PARK on right near beginning of straight stretch of road near wooden
       post inscribed "Rattlesnake Hill."

       STOP 2   RATTLESNAKE HILL

       The small quarry on the southeast side of the hill is the type-locality
       for the BLUE HILLS PORPHYRY. Somewhat back on the top of the hill the
       bedrock is Quincy Granite. To a first approximation the contact is
       gradational, the granite at this locality being somewhat porphyritic,
       but if your eyes become sufficiently attuned to the rock-types it is
       possible to locate a sharp line of contact. Over several meters the
       Quincy Granite grades through a fine-grained to porphyritic variety,
       thence over a few centimeters into true Blue Hills Porphyry. The
       actual line of contact is marked by an abundance of rhomb-porphyry
       xenoliths in the granite. The best exposure of this contact is near
       the west end of the small quarry in a loose slab that has rotated
       slightly out of position.

       Even here in the type-locality, the BLUE HILLS PORPHYRY is easily mis-
       taken for holocrystalline, fine-grained granite, but on closer examin-
       ation (especially in thin-section) the rock is seen to consist of
       coarse grains of microperthite and quartz in an aphanitic matrix
       (41% microperthite, 12% quartz, and 47% matrix here). Thin-sections
       show significant amounts of riebeckite and aegirite intergrown with
       the matrix, and minor aenigmatite, magnetite, hematite, zircon, fluor-
       ite, astrophyllite, and calcite. The mineralogy, the major-element
       chemistry, and the trace-element distribution patterns of the Blue
       Hills Porphyry and the Quincy Granite are closely similar to each
       other and distinctive compared to other New England granites. These
       features strongly suggest the Blue Hills Porphyry and the Quincy
       Granite are comagmatic and hence of about the same age. If the Blue
       Hills Porphyry is the chilled border phase of the Quincy Granite it
       should appear slightly the older of the two units. Unfortunately, the
       detailed field relationships do not permit a clearcut determination of
       the relative age of the two units (see also STOP 4).

1.0   continue south on Wampatuck Road

1.5   RIGHT at junction onto Chickatawbut Road

1.6   PARK in small parking areas on right or left

       STOP 3A Walk back to the junction of Wampatuck and Chickatawbut Roads,
       then south on trail (old road) about 100 meters (yards). To the left
       is a rock-knob with a vertical face on the south side; examine the face.
       The knob is mostly Blue Hills Porphyry but the face shows a fine-grained
       rock that is probably a screen or large inclusion of APORHYOLITE.
       Examine the porphyry on the top of the knob; the aphanitic matrix
       characteristic of the porphyry is more evident here than at the previous
       stop. The porphyry appears chilled against the Aporhyolite.

       STOP 3B Return to cars and follow trail south to summit of rock-knob.
       On the way up you cross a thin screen of Aporhyolite in the porphyry
       and can closely approach a contact on the south side of the screen.
       The porphyry on the summit of the knob contains digested xenoliths of
       the Aporhyolite.

STOP 3C   Return to parking area and follow trail north of road to
summit of Wampatuck Hill.   (Take LUNCH to eat on summit with good
views over Boston.)   The trail uphill is mostly in Blue Hills Porphyry
then crosses a contact into the APORHYOLITE, which crops out on the
top of the hill.   The volcanics (Aporhyolite) here were designated
by Kaktins (1976) as the Wampatuck Hill Ash Flow, which he subdivided
into the following units: a basal clastic-rich eutaxitic zone; a
densely-welded zone with few phenocrysts and few spherulites; a
eutaxitic zone with abundant flattened pumice; and an upper phenocryst-
rich zone with minor, but relatively uncompressed pumice.   The upper-
most unit is the one in contact with the porphyry, the probable top
of the flow having been cut out here;   down-section is to the north
at this locality.

1.6   continue westward on Chickatawbut Road

1.8   Blue Hills Reservoir on Left

2.8   Chickatawbut Hill Road on LEFT (narrow paved road with "No Trespassing"
        Sign to optional Stop 4 (mileage not included in log).   Obtain per-
        mission from the MDC Police (station about two miles west on Chicka-
        tawbut Road) to visit this stop.   Also inquire at the Trailside Museum
        west of Blue Hill to see if you can get inside the fence once reaching
        the top of the hill.

        STOP 4 (OPTIONAL)   SUMMIT OF CHICKATAWBUT HILL   Good views over Boston
        Basin.   On south side of hill just inside fence is one of the critical
        localities for studying relationships between the Quincy Granite and
        the Blue Hills Porphyry (see sketch of plane-table map).   This locality
        shows an elongated patch of fine-grained granite in the porphyry that
        can be interpreted either as a disjointed dike of granite cutting the
        porphyry or as xenoliths of granite included in the porphyry.   We have
        not been able to conclude which.   Even if this could be decided, it
        must still be determined whether the granite is true Quincy Granite.
        This situation typifies the difficulty of determining the age of the
        Blue Hills Porphyry relative to that of the Quincy Granite.   Because
        the critical exposures are in brush, on a cliff, inside the fence, this
        stop is not suitable for large groups and will probably not be visited
        on the trip.

2.8   continue west on Chickatawbut Road

3.1   Park on LEFT at junction of Chickatawbut Road and Randolph Ave for

        STOP 5   Blue Hills Porphyry near contact with Aporhyolite.   Several
        outcrops of porphyry are exposed southeast of the intersection.   The
        porphyry is variable in character, but typically shows an abundance
        of fine-grained matrix suggesting that it has been chilled in the
        vicinity of the Aporhyolite.   The contact is mapped under Randolph Ave
        but good exposures of the Aporhyolite cannot be seen in the vicinity.

3.1   RIGHT onto Randolph Ave northbound; proceed north past golf course.

4.2   PARK on RIGHT at gravel road (don't block road) opposite yellow and
        white house on left.   Walk about 200 meters (yards) east on gravel
        road to poorly marked trail going uphill (north) for

        STOP 6   BRAINTREE ARGILLITE, outcrops of which are visible on the slope
        of the hill.   The outcrops can be reached directly from where they are
        first seen from the gravel road but it is worth searching out the trail

(beyond where the outcrops are first seen) to avoid traversing through brambles. (The description of this stop is based partly on the description of Chute (1964) Stop 14.)

The outcrops along the slope of the hill are hornfels representing the Middle Cambrian BRAINTREE ARGILLITE. This unit has yielded some of the largest trilobites known, Paradoxides harlani (the loose materials at STOP 1 being much better for possible collecting than the present stop, however). These are Acado-Baltic fossils whose faunal-province relationships are part of the evidence for the closing of the Iapetus ("proto-Atlantic") Ocean during the evolution of the Appalachian Mountains. It is generally agreed that the Braintree Argillite occurs as xenoliths and roof-pendants in the Blue Hills Igneous Complex, which is thus younger than Middle Cambrian. At this locality the Braintree Argillite is cut by diabase dikes that appear to be older than the Quincy Granite. Further uphill is a 30 m wide apophysis of fine-grained Quincy Granite with abundant inclusions of rhomb-porphyry and argillite, and at the top of the hill is the main body of the Quincy Granite marked by abundant inclusions and an intrusion breccia.

4.2   return to vehicles: U-TURN, returning south on Randolph Ave.

5.9   intersection of Randolph Ave and Chickatawbut Road; continue south on Randolph Ave (Route 28)

6.3   fifty meters (yards) past signs for Route 128 PARK on right or pull into parking loop on left (when you leave you will continue south on Randolph Ave).

STOP 7 CONTACT BETWEEN BLUE HILLS PORPHYRY AND PONDVILLE CONGLOMERATE at interchange between Routes 28 and 128. This roadcut, constructed after the completion of most of Chute's field work, is one of the most controversial outcrops in the Boston area. Walk south along the right side of Randolph Ave then proceed to the right up the exit from Route 128. Briefly examine the Blue Hills Porphyry, then work your way fairly quickly along the outcrop until you are well up into the Pondville Conglomerate. Now decide where you would put the contact between the two units (in a group it is instructive to put this to a vote).

The PONDVILLE CONGLOMERATE is the basal unit of the Norfolk Basin sequence, the higher members of which contain Carboniferous fossils. The conglomerate (here called the Giant-Pebble Conglomerate) contains clasts of Blue Hills Porphyry, felsite (presumably Aporhyolite), quartzite, and argillite. Clasts of normal Quincy Granite have not been reported, although clasts of fine-grained hornblende granite can be found. At the top of the section the clasts are well-differentiated from the matrix, and lower in the section one can find an irregular but discrete surface below which the clasts no longer "pop out" from the matrix. Most workers, ourselves included, regard this surface as a non-conformity separating the Carboniferous Pondville Conglomerate from an older Blue Hills Porphyry.

This leaves a curious zone with pseudo-cobbles (greenish spheroids of microperthite, quartz porphyry in a matrix of generally finer-grained reddish porphyry) separating the Pondville from the normal, massive variety of the Blue Hills Porphyry. Chute interpreted this as a zone of spheroidal weathering and residual soil below the non-conformity.

D.R. Wones drew our attention to features suggesting a certain amount of transport of the pseudo-cobbles. They differ from each other and from the matrix in the details of phenocryst abundance and composition, in such a way that it appears unlikely that all the differences could be caused by weathering. He raised the possibility that the porphyry at this locality might be a Carboniferous volcanic unit grading upwards into the true conglomerate through a zone containing volcanic clasts in a welded volcanic matrix, the outcrop possibly having formed as a lahar.

For the reasons given in the discussion, we conclude that the exposure contains a non-conformity separating Silurian (?) Blue Hills Porphyry from Carboniferous Pondville Conglomerate. We interpret the zone of pseudo-cobbles as an emplacement breccia within the porphyry -- a zone in which fragments were broken off from the porphyry and transported in a gas-rich matrix that subsequently chilled. Note how the clasts of porphyry appear to fit together as the pseudo-cobble zone grades downwards into the massive porphyry. By this interpretation it is only a coincidence that the zone appears directly beneath the non-conformity at this stop. Sayer has noted breccia-zones elsewhere in the porphyry although none are so evident as the one seen here. Perhaps some of the primary contrasts between the pseudo-cobbles and the matrix have been enhanced by weathering below the non-conformity.

If time and interest permit, one may see the overlying Wamsutta Formation on the opposite side of Route 128. Return to Route 28 and walk through the underpass, skirt the fence then backtrack to walk along the canal to the Wamsutta roadcut in the exit loop. Note the cross-beds, channel-fill, and other sedimentary features, and study the oxidation-reduction reactions represented in the red and green coloration. Can you decide if the reduced zones (green) are localized around carbon-rich plant-fragments?

The SHORTEST RETURN TO BOSTON is by Route 128 EASTBOUND; south on Randolph Ave under bridge, RIGHT for entrance to 128 Eastbound, thence eastward to Southeast Expressway Northbound. To return to Boston University exit at Massachusetts Ave and retrace route followed in the morning. (Note that the desired exits from both Route 128 and the Expressway are made from the LEFTHAND lanes.)

A considerably more distant route, but one that may save time in heavy traffic is to proceed WESTWARD on Route 128 (enter just beyond where cars are parked) backtracking into Boston on the Massachusetts Turnpike. Along this route you pass cuts of various units of the Blue Hills Igneous Complex, followed by cuts of the Late Precambrian Dedham Granodiorite, followed by cuts of Roxbury Conglomerate near the westward margin of the Boston Basin.

GEOLOGIC RELATIONSHIPS OF THE SOUTHERN PORTION OF THE BOSTON BASIN FROM THE BLUE HILLS EASTWARD

by

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and

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The structural, stratigraphic and petrologic relationships in the Weymouth and Cohasset quadrangles are the principle subjects of this field trip. The Dedham Granodiorite is the oldest rock in this area and varies petrologically from granite to granodiorite to diorite. Overlying the Dedham Granodiorite are the Lower Cambrian Weymouth Formation and the Middle Cambrian Braintree Argillite. The intrusive contact between Ordovician Quincy Granite and Braintree Argillite will be noted.

At some locations the Weymouth and Braintree Formations are missing and the Dedham Granodiorite is overlain by the Boston Bay Group sedimentary and volcanic rocks of Pennsylvanian(?) age. The unconformable contact between these two formations is exposed at two locations.

Major faults trend east-west and minor faults are oriented north and south. Fault contacts between the Braintree Argillite and the Quincy Granite, and Braintree Argillite and Dedham Granodiorite are well exposed. The Hingham Anticline plunges steeply to the west.

The general geology of the area has been well described elsewhere in this volume by Marland Billings. Structural descriptions applicable to this field trip include the Central Anticline, Roslindale Syncline, Mattapan Anticline, Hyde Park Syncline, Houghs Neck Anticline and the Hingham Anticline. Faults include the Blue Hills Thrust which, from Milton to Nantasket, is the northern boundary of the Quincy Granite; the Ponkapoag Fault which brings Precambrian Dedham Granodiorite against Braintree Argillite and Carboniferous Boston Bay rocks; and the Stony Brook Fault which is a cross fault oriented generally north-south.

Petrologic descriptions of the rocks to be viewed on this field trip are, from oldest to youngest, as follows:

Dedham Granodiorite: Precambrian. Medium-to coarse-grained, light grey to pinkish rock, often porphyritic. Quartz, microcline and plagioclase are the principle constituents. Alteration minerals include chlorite after hornblende and biotite, epidote and sericite in the feldspar grains. The greenish-white color of

some of the plagioclase is due to epidotization. Late stage
aplite, composed of microcline and quartz, and epidote and quartz
are present in fracture fillings.

Weymouth Formation: Lower Cambrian. This formation contains red,
green and purple shales with greyish green siliceous layers.
Characteristic nodules occur in layers with the long axis of the
nodules parallel to stratification. These nodules often have
pinkish green calcareous centers which may weather out leaving
rims of siliceous material. Olenellus fossils are found in this
rock.

Braintree Argillite: Middle Cambrian. Greenish-grey to black,
fine-grained rock is composed of chlorite, epidote, sericite,
quartz, untwinned feldspar, leucoxene, and graphite (Chute, 1969).
The rock is locally affected by thermal metamorphism of the
Quincy Granite intrusion which increases the chlorite and epidote
content giving the rock a definite green tint. When associated
with faulting, the Braintree is black and highly distorted and
may be metamorphosed to hornfels. *Paradoxides harlani* is the most
distinctive fossil of this formation.

Blue Hills Complex: Ordovician(?). The Quincy Granite is des-
cribed by Chute, 1969, as a "massive, medium- to coarse-grained
nonporphyritic, grey to dark bluish-grey granite, locally pink,
red, or dark green due to hydrothermal alteration". Constituent
minerals include microcline microperthite, quartz, reibeckite and
aegerine. Accessory minerals include magnetite, pyrite, fluorite,
zircon, sphene, apatite and allanite. Zartman and Marvin (1971)
dated the Quincy Granite as Late Ordovician. For the most part,
the Quincy Granite viewed on this trip will be the fine- to
medium-grained, pink to red variety.

Boston Bay Group: Pennsylvanian(?). The Boston Bay Group
includes the Roxbury Conglomerate, which is divided into three
members, and the Cambridge Argillite.

    Brookline Member: Contains conglomerate, argillite, sandstone
    and melaphyre. The conglomerate has a grey, sandy matrix with
    well-rounded clasts from 0.5 - 40 cm in diameter. The argil-
    lites are pink to grey-green and split into thick slabs. Sand-
    stone is fine- to medium-grained, white to red rock. The
    melaphyres are composed of amygdaloidal basalts and andesites,
    felsites and agglomerates.
    Dorchester Member: Well-stratified conglomerate with red and
    purple sandstone.
    Squantum Member: Coarse-grained conglomerate with locally very
    large clasts and sandy matrix. Clasts are sub-rounded to angular.
Cambridge Argillite: Fine-grained grey to grey-brown rock with
clay- to sand-sized grains. Thinly-bedded, slightly calcareous,
may be slatey.

Figure 1. Sketch map showing stops.

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7½ minute topographic maps available for the trip are:
Weymouth, 1971; Hull, 1971; Nantasket, 1974; Blue Hills, 1971;
and Cohasset, 1961. The advance copy of the Cohasset may be
ordered in black and white only.

The only published geologic quadrangle map of the area is
the Bedrock Geology of the Blue Hills Quadrangle, Norfolk, Suf-
folk and Plymouth Counties, Mass., GQ-796, 1969.

ROAD LOG

Route 3 (Southeast Expressway) south from Boston. Note Quincy
granite quarries just before Exit 24. The first commercial rail-
way was constructed here in 1820 to transport the granite for
Bunker Hill Monument in Boston.

At Exit 24 (Furnace Brook Parkway), leave the expressway, bear
left to pass under the highway, and bear right to the traffic
light. See Figure 1.

MILEAGE

Cum. Pt/Pt.

	.5	At traffic light, turn right onto Copeland St.
1.0	.5	At traffic light Copeland becomes Water St.
1.6	.6	At traffic light, turn right onto Franklin St. At next traffic light, bear left on Franklin St. NOTE red houses on the corner are the birthplaces of John and John Quincy Adams.
2.0	.4	At blinker, turn left onto Kendrick Ave. Sign for Faxon Park.
2.2	.2	Turn right into Faxon Park. Continue through picnic and playground and on through gateposts to overlook.
2.7	.5	STOP ONE. FAXON PARK. This point marks the beginning of the field trip and serves two purposes. First, outcrops of the Quincy Granite are abundant. Secondly, there is an excellent vista of the Fore River Basin and the area in which Stops 2-7 will be made (Fig. 1). Hull Gut, the southern limit of Boston Bay, is in the background to the right of the blue water tower. On a clear day, Marblehead, the northern limit of Boston Bay is visible in the distance over the white church in the center foreground. Follow park road down to the right.
3.1	.4	Turn right onto Faxon Park Rd.

3.3	.2	Turn right onto Quincy Ave.

3.9   .6   At traffic light, turn left onto Southern Artery.

STOP TWO. FORE RIVER MOTORS PARKING LOT. The contact between Braintree Argillite and Quincy Granite is well displayed here. Actually this is a double contact since both the north and south faces of the Braintree are exposed and the total thickness is about 3.7 m. The rock is highly cleaved and displays properties indicative of stress which relates to the intrusion of Quincy Granite. The granite is the fine-grained pinkish phase but locally is very dark and contains small xenoliths of Braintree Argillite.

4.1   .2   At traffic light, turn right onto South St.

4.3   .2   Park on left side of street in open lot.

STOP THREE. BENTS CREEK FAULT. The Bents Creek Fault is a minor fault graben in which the especially promi-nent fault surface on the northern side of the graben strikes from 96° to 101° and dips 53° to 70° to the south. The downthrown block contains Argillite (Ver-ma, 1973) while the upthrown blocks are composed of Quincy Granite. This graben is well displayed geo-morphically as the softer argillites are more rapidly eroded than the resistant Quincy Granite.
Continue on South St.

4.5   .2   Turn right onto East Howard St.

4.8   .3   Note contact between Quincy Granite and Braintree Argillite. The granite is fine-grained, pinkish,and displays iron oxide staining. Near the contact the fine phaneritic texture becomes porphyritic aphanitic with feldspar phenocrysts in a mafic matrix. The argillite is greenish-grey, massive and fine-grained. Directly across the street from this outcrop is the General Dynamics Shipyard in which the Haywards Creek Quarry was located. Many fine specimens of Para-doxides harlani were found in this quarry (Lord, 1972).
Continue on East Howard St.

4.9   .1   At traffic light, cross Quincy Ave. Continue on East Howard St.

5.1   .2   Bear left onto Shaw St. NOTE outcrops of granite as you go over the hill.

5.8   .7   Turn left onto Allen St.

6.0   .2   STOP FOUR. ALLEN STREET. Contact (not exposed) between Braintree Argillite and pink Quincy Granite.

6.2   .2   Turn right onto Quincy Ave (Route 53).

6.4   .2   At traffic light, turn left onto Commercial St. NOTE large outcrop on right behind Sacred Heart School. The rock is altered and highly fractured.

6.6   .2   <u>STOP FIVE</u>. <u>COMMERCIAL STREET-WEBB PARK RAILROAD CUT</u>. Park on northwest side of the street in open lot. This stop displays the Ponkapoag fault which appears as a normal fault striking 65° and dipping 61° north. Braintree Argillite is on the downthrown block to the north and Dedham Granodiorite to the south. The Dedham is texturally atypical, displaying an aphanitic texture in places which is micrographic in nature. The Braintree is highly distorted with drag folds. Continue on Commercial St. east. Hills on right are Dedham Granodiorite.

7.4   .8   Turn left onto Narragansett Ave.

7.6   .2   <u>STOP SIX</u>. <u>IDLEWELL RAILROAD CUT</u>. The contact between the Braintree Argillite to the north and the Quincy Granite to the south is exposed in this cut. This is a thrust fault showing pink Quincy Granite thrust over Braintree Argillite. Tension cracks occur in the Braintree nearly perpendicular to cleavage. The color of the Braintree is black to greenish-grey.

7.8   .2   Return to Commercial St. Turn left.

8.0   .2   Bear left onto Church St.

8.3   .3   At traffic light, turn left and continue under railroad tracks.

8.4   .1   Bear left around rotary to Norton St.

8.8   .4   Norton St. becomes Pearl St.

8.9   .1   Turn left onto Evans St.

           One block. Turn left onto Brewster St.

9.1   .2   <u>STOP SEVEN</u>, <u>BREWSTER STREET AT MILL COVE</u>. This stop must be made at low tide. This is the type locality of the Weymouth Formation. The rock is fine-grained, green to purple argillite with siliceous and calcareous nodules that tend to be partially or completely dissolved out of the rock. At this site copper mineralization has been reported in the Weymouth (C. A. Kaye, 1975, personal communication). Finely laminated bedding and nodules in layers show strike of 102°and dip of 73° north. NOTE granite outcrop on point across inlet.
Return to Evans St.

9.3   .2   Turn left onto Evans St.

10.3 1.0   At traffic light, turn right onto Route 3A (Bridge St).
            NOTE Kings Cove across 3A. One branch of the boun-
            dary fault goes through here (Lord, 1972).

11.8 1.5   STOP EIGHT. GREAT ESKER PARK. Park just before
            bridge near movie entrance. Bring your lunch as we
            walk along one of the few remaining examples of an
            esker in Weymouth. The Town of Weymouth, in order
            to preserve this glacial feature, has made it a town
            park, an excellent example of townspeople with the
            vision to protect historic, in this case geologic,
            landmarks which are irreplaceable.
            Return to Route 3A south.

12.5 .7   STOP NINE. RAILROAD CUT AT SHIPYARD. Park car by
            small food stand. The sequence of rocks displayed
            in the east-west railroad cut behind the food stand
            is volcanic rocks grading upward to fine-grained
            sediments to conglomerates. One stratum near the
            top of the sequence is distinctly calcareous (C.A. Kaye,
            1975, personal communication). This sequence, part
            of the Roxbury, is stratigraphically near the base of
            the Boston Bay Group. Clasts to 7.6 cm are found. The
            sequence dips to the west.
            Continue on Route 3A south.

12.8 .3   At traffic light, turn right onto Pottler Rd.
            Cross railroad tracks.

12.9 .1   STOP TEN. POTTLER ROAD QUARRY. Small dirt road into
            abandoned quarry on right side of road beyond con-
            crete block building. The contact here between the
            Dedham Granodiorite and the overlying volcanic con-
            glomerate represents an unconformable surface.
            Continue on Pottler Rd.

13.2 .3   Turn right onto Beal St.

13.3 .1   STOP ELEVEN. BEAL STREET OUTCROP. Outcrop is in
            front of building on northeast corner of Beal St. and
            Churchill Rd. Alternating layers of the Roxbury
            containing argillite and conglomerate, striking 35°
            and dipping 83° to the south make up this interesting
            outcrop. Clasts in the conglomerate are smaller and
            more angular than at Stop Nine. Layering is usually
            well displayed with strata thickness of 1.5 to 3 m.
            Distinctive minor faulting is transverse to stratifi-
            cation.
            Proceed south on Beal St., bearing right at fork.

14.5 1.2   Turn right onto South St.

14.6 .1   Turn right into Bare Cove Park. Sign for Hingham
            School Department.

14.9   .3   Bear right at fork and stop beyond building 179.
STOP TWELVE. HINGHAM AMMUNITION DEPOT. The unconform-
able contact between Precambrian Dedham Granodiorite
and the Paleozoic volcanic rocks is classically dis-
played here. This unconformity is probably comparable
to the unconformity between the Dedham and the overlying
volcanics at Nantasket Beach (C.W. Wolfe, 1975, personal
communication). The volcanic rocks from the unconfor-
mity upward are felsite, volcanic conglomerate and
amygdaloidal basalt. Two very significant aspects of
this stop are the exposure of the unconformity and
the basal volcanic conglomerate with greenish matrix
and angular clasts varying from 15 to 30 cm in dia-
meter, some of them of granitic rock resembling the
Dedham.
Continue down the road, bearing left at multiple inter-
section. Go through gate. Continue bearing right
at intersections to Building 97.

15.6   .65   STOP THIRTEEN. BOSTON BAY SECTION. This stop will
involve walking across the stratigraphic section of
the lower and middle portions of the Boston Bay Group.
The lower unit is volcanic with amygdaloidal texture.
Overlying this is a thick conglomerate with large
rounded granite clasts. As one proceeds upward in
the column, the sediments become finer, changing to
fine conglomerates, sandstones and argillites. Strata
tops are definitely indicated at one outcrop and
confirm the steeply westerly plunging anticline (Bil-
lings, this volume).
Reverse direction and return to park gate.

16.5   .96   At gate, turn left onto Fort Hill St. Fort Hill St.
becomes South St. which in turn becomes North St.

17.9   1.4   Turn right onto Route 3A.

18.1   .2   At rotary, turn onto Summer St. Follow signs for
Hingham District Court.

18.9   .8   At second traffic light, turn left onto Washington St.
NOTE large erratic of Dedham Granodiorite on right at
the traffic light.

19.4   .5   STOP FOURTEEN. COURTHOUSE QUARRY. Dirt road beyond
courthouse leads into quarry. Leave vehicles beside
Washington St. This quarry shows different phases of
the Dedham and some of the results of diastrophism
of two or more separate events. See Figure 2.
Reverse direction and return to rotary traffic.

20.7   1.3   At rotary, turn onto Route 3A south.

21.9   1.2   At second traffic light, turn onto East St.(Route 228,
east).

22.1   .15   Turn onto Weir St.

22.5   .4   STOP FIFTEEN. WEIR STREET QUARRY. The petrologic
characteristics of the Dedham Granodiorite are quite
variable in the Cohasset area. At this stop two
distinct variations may be noted. The first is
"normal" Dedham, although it may be more appropriately
called a coarse-grained binary granite, with quartz
and K-feldspar as the main constitutents. This light
colored variety may be contrasted with a dark unit
21 m away which contains quartz, feldspars and mafic
minerals such as amphibole and chlorite. The rock also
shows evidence of at least one deformation with flow
foliation indicated by the parallel arrangement of
feldspar laths. Left lateral offset of aplite frac-
ture filling is also noted.
Return to Route 228 west.

22.7   .2   Turn right onto East St.(Route 228 west).
Proceed on Route 228 through South Hingham, noting
Dedham outcrops.

25.7   3.0   Turn right onto Cushing Street. Bear left at fork.

27.8   2.1   At traffic light, turn right onto Route 53 (Whiting St.)

28.7   .9   STOP SIXTEEN. PLYMOUTH GRANITE QUARRIES. Park on
roadside. This quarry is the only building stone
quarry presently operating in this area. The rock is
a fine-grained, light grey granite composed of light
grey feldspar (mostly plagioclase with minor micro-
cline), colorless to smokey quartz and very minor
amounts of epidote, pyrite and magnetite (Crosby and
Loughlin, 1910). This granite, locally called Wey-
mouth Granite, may be equivalent to the Westwood
Granite (Chute, 1969). One of the more unusual
characteristics of this rock is that it has a "remark-
ably perfect parallel joint structure". The joints of
one system are about vertical, nearly perfect and
divide the granite into sheets that usually vary
from 15.2 to 60 cm thick. This feature of the granite
is referred to in the industry as "seam-face granite"
and has obvious economic advantages in the working and
utilization of this hard, durable rock.
Continue on Route 53 north.

29.5   .8   At second traffic light, turn left onto Middle St.
Take first right onto Winter St.

30.1   .6   At traffic light, turn left onto Route 18.

30.2   .1   Take first right onto Route 3 north, Southeast Expressway.
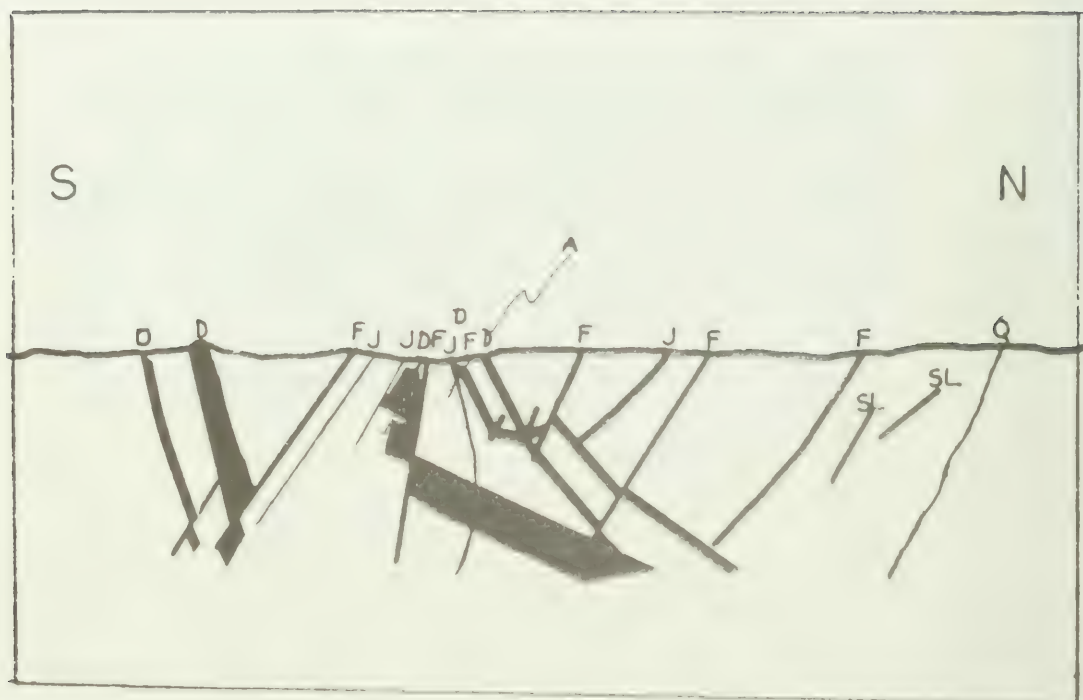
Figure 2. STOP FOURTEEN. WEST WALL OF QUARRY BEHIND
           HINGHAM DISTRICT COURTHOUSE.

Exposure shows evidence of complex fracturing and faulting.(F).
To the north the rock is coarse-grained granodiorite with large
pink microcline phenocrysts. South of the two mafic dikes (D)
on the left, the rock is much finer-grained. The dike marked (AL)
is pink aplite. The dikes occupy the northerly dipping joint set.
Movement is evident along the southerly dipping set, and one
joint contains a quartz vein (Q). Slickensides on this set are
epidotized.
Scale: The large central dike is 2.05 meters thick.

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SURFICIAL GEOLOGY OF BOSTON BASIN

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(Topographic maps: Boston North, Boston South, Hull, Lexington, Newton quadrangles)

Much depends on whether or not revealing foundation excavations are open and available for our inspection. The following stops will comprise the trip without excavations. Otherwise one or more of these stops will be dropped from the itinerary to allow time for unscheduled stops.

No road log is given because in a heavily built-up city this serves little purpose.

Starting point is Boston University parking lot.

Stop 1. Long Island, Boston Harbor (Hull quadrangle)

    A.) View of the harbor from hospital parking lot to see the many drumlin islands.

    B.) Middle drumlin. This is a compound drumlin made up of 3 coalesced drumlins, side by side. We will look at a cliff cut in the middle drumlin which shows good stratification and non-till zones. We can also see oxidized and non-oxidized till and, if we are lucky, we can collect shells from the till.

    C.) West Head. This cliff shows some stratification and deep oxidation. We will discuss probable original shape and later glacial modification of shape. The rock types represented in the clasts and the location of the probable source beds will be discussed. The erosional processes working on this cliff will be discussed and the net rate of erosion.

Stop 2. Chapel Rocks, Squantum (Boston South quadrangle)

    Type locality of the Paleozoic Squantum "tillite". We will discuss whether it is a tillite.

Stop 3. Lunch, at Howard Johnson No. 1,

Stop 4. Boston Common with view of Beacon Hill.

    A.) Original topography, Hill, Boston Common, Public Garden

    B.) Structures and deposits in two morainic systems

C.) Dating the glacial readvances

Stop 5. We will trace the line of the Back Bay moraine and Fresh Pond moraine in Cambridge (Boston North quad.).

Stop briefly at Observatory Hill (Lexington quadrangle)

Stop 6. South side of Fresh Pond, Cambridge (Lexington quadrangle)

Stop 7. Mt. Auburn Cemetery, Cambridge (Newton quadrangle)

Stop 8. Foster St., Brighton (Newton quadrangle)

Striated outcrop that shows 3 directions of ice flow.

Stop 9. Jamaica Pond moraine (Boston South quadrangle)

This small moraine is at the head of the Jamaica Plain outwash. Jamaica Pond is a large kettle and may mark the southern advance of a late Wisconsin readvance, possibly Beacon Hill, slightly less possibly, the Back Bay readvance.

Return to parking lot by way of Harvard Medical School area and Parker Hill drumlin.

THE EFFECTS OF GEOLOGY, TOPOGRAPHY, AND DISTURBANCE ON THE SOILS AND VEGETATION OF THE MIDDLESEX FELLS, MASSACHUSETTS

by

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Introduction

The Middlesex Fells became a reservation in 1896, when it was acquired by the Metropolitan Park Commission. Prior to that time the area had a long history of abuse. Its timber resources were used for a variety of domestic, industrial, and even military purposes. Parts had been cleared for agriculture. All of it was regularly used for foraging livestock. Its bedrock, particularly the Medford Diabase, was quarried for building the road materials. Fires were frequent.

The present landscape still shows the effects of the earlier abuse. Quarries and road cuts gave a sometimes incongruous roughness to a landscape generally smoothed by glaciation. The vegetation mosaic is now different in character to that at the time of settlement. The present structural and compositional variations are difficult to interpret, but appear to reflect man-induced disturbance.

Geology and Geomorphology

Little space is devoted here to geology and geomorphology. For details, you should consult Skehan's (1975) excellent little field guide.

Much of the surface of the Fells is covered by a thin veneer of glacial drift. Bedrock is generally exposed on ridges, and in road cuts and quarries (see the I-93 cut at Pine Hill). Three bedrock types are common in the Fells. The Precambrian basement complex is represented by the Dedham Granodiorite, a light-colored plutonic rock. Two sets of volcanics have cut through the basement materials. The Middle Paleozoic Lynn Volcanics are fine-grained, generally buff-colored. Intruding through the Lynn Volcanics and the Dedham Granodiorite are many Triassic dikes. The dark rock is common throughout the Fells. Its intrusive character is best illustrated in the I-93 road cut on the east side of Pine Hill (seen on the way from Bellevue Pond to the Spot Pond Area.)

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FIGURE 1

FIGURE 2

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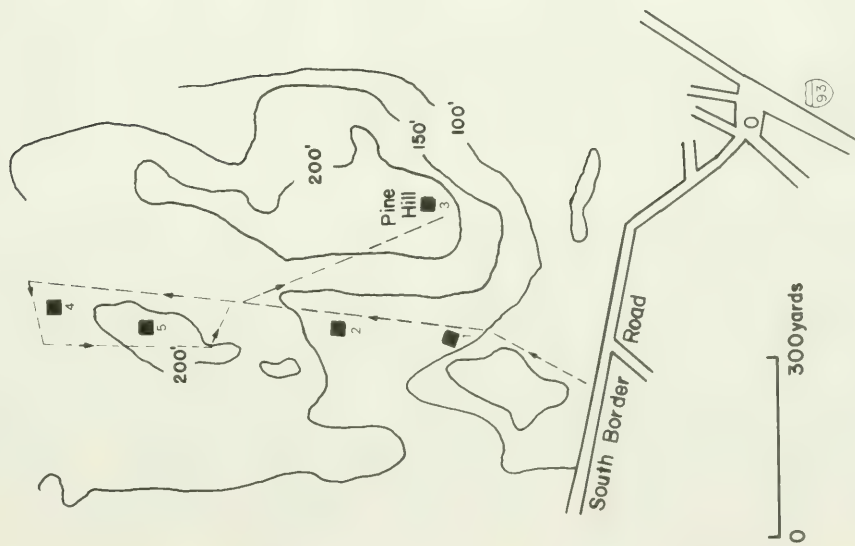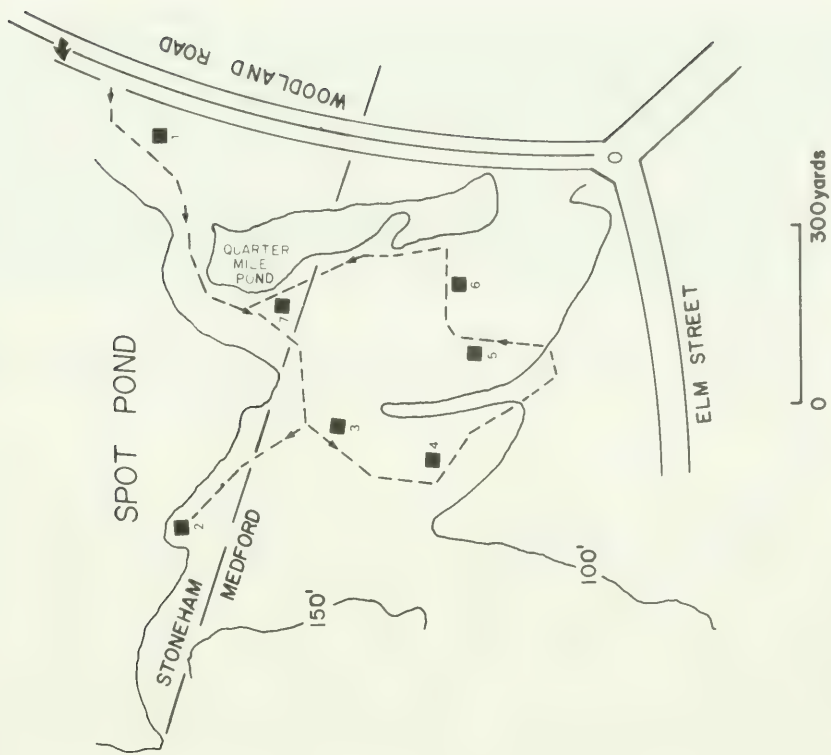
The largest of these dikes is the Medford Dike. The path north from Bellevue Pond runs along it. The rock is exposed in the many small quarries along the path. The dike rock, although much younger than the Lynn Volcanics and Dedham Granodiorite, has been eroded into a well-defined valley.

Glaciation has given the Fells its thin veneer of till and the northwest-southeast orientation of many of its bedrock ridges. This orientation is more northerly than that of the drumlins in the Boston Basin. The effects of ice movement are clearly seen in the bedrock exposures at Pine Hill (Stop 3).

Disruption of drainage in glaciation has been partly responsible for the lakes and swamps throughout the Fells. However, many of the lakes are man-made or man-modified.

Soils

Except for areas of organic soils in low, poorly drained sites, the soils of the Middlesex Fells can be classified as podzolic soils. Such soils are characterized by surface accumulations of acidic organic materials, by their low saturation due to removal of soluble minerals by leaching, and by their often spectacular striped appearance. They develop best in coarse, well-drained materials under conifer-hardwood forest cover. Some kinds of vegetation are particularly conducive to podzolization. Coniferous trees generally produce an acid surface organic layer. This 'mor' humus layer is obvious under the hemlock and pine areas near Spot Pond (Stops 1 & 5).

Podzolization is a combination of processes that involves translocation of organic matter, and iron and aluminium for the upper part to the lower part of the solum (Buol, Hole and McCracken, 1973). In well-developed podzols, the movement produces a distinctively banded soil with a dark A_1, light-colored, eluviated A_2 and a red B, where the illuviated sesquioxides are deposited. Nowhere in the Fells do the soils show this clear horizonation.

The mineral soils, where classified, are all members of the Gloucester Series. These soils develop on rolling topography in glacial till derived largely from igneous and metamorphic rocks. Most are stony, well-drained, and thin, with no marked textural profile. Variations in depth and character throughout the Fells are primarily the result of landscape position and vegetation type. The higher parts of the landscape have very thin soil cover with many bedrock exposures. In lower areas, the soils are deeper and wetter. Thos soils developing under hardwoods are less acid than those under white pine and hemlock. The surface humus under hardwoods is generally thinner and more easily decomposed than the 'mor' surface layer under the conifers.

All of the soils have low pH values (4-5.5), and are deficient in potash, nitrogen and phosphorus.

The Gloucester Series occupied upland surfaces in eastern Massachusetts (Figure 3). It is generally the highest soil in a catena that includes Whitman and Essex Soils (wetter sites on glacial till), Merrimac, Scarboro and Hinckley soils (an glacial outwash), and Po unk and Ondawa soils (on recent alluvium).

According to the 7th Approximation, the Gloucester Series are classified as Entic Haplorthods; Spodosols (podzols) that lack distinctive horizons. They have some similarities with the Entisols, young soils with only incipient horizon development.
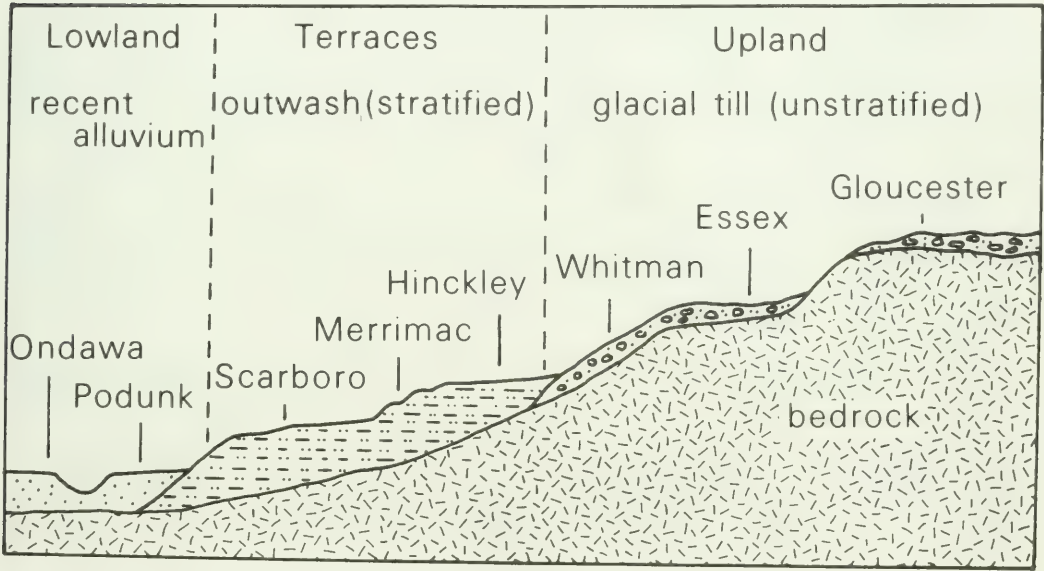
Figure 3. Typical soil sequence in eastern Massachusetts.

Vegetation

The vegetation of the Middlesex Fells is a composite of com-
munities that vary with landscape position and with the frequency
and nature of disturbance.

The vegetation at the time of settlement was a mosaic domin-
ated by white pine and hemlock. Hills and ridges were often cover-
ed with cedar, oak and hickory with admixtures pine. Canoe
birches fringed swampy areas where red maple, grey birch and white
cedar dominated. In 1632, Winthrop observed that the Spot Pond
area was thick with pine and beech. The change to the present
hardwood dominated woodlands can be attributed to man-induced dest-
ruction and disturbance rather than to successional changes.

Exploitation of the area's timber resources led to general
deterioration of the woodland, and changes in its character due
to the differential use of some species. White cedar, once common
in the bog sites in the Fells, was quickly eliminated. The white
pine and hemlock was used for shingles, clapboard, posts, and ship-
building from the late seventeenth century. The canoe birches
were cut for shoe pegs. Timber of all species was used for domes-
tic fuel and later for industry such as the nearby brick-making
operation in Medford (Met. Park Commission, 1895). The Pine Hill
area was particularly abused. It was stripped in 1775-6 to pro-
vide wood for Washington's army and cleared again in 1855 (Medford
Historical Society, 1935).

Some clearance for pasture was attempted. Most cleared areas
had been abandoned in the late nineteenth century, although some
parts of the Fells were still classified as 'bushy pasture' when
the area was taken over by the Metropolitan Parks Commission.
Cattle were turned out into the woods to forage for acorns, chest-
nuts, and beech mast. The browsing probably had an important
impact on the regeneration of stands.

Fires were frequent. In the Fells, there were generally of
small extent, but common. Winchester recorded eleven fires in
fourteen years, Stoneham seven fires in seven years in the early
part of last century. By 1880, much of the area was classified
as brush (Wright, 1893). Frequent burning may have been respon-
sible for the limited regeneration of hemlocks, and for the impor-
tance of oaks in the present forest communities. Although the
frequency of fires decreased after 1894, occasional fires have
continued to modify community structure and composition. The area
south of Spot Pond was badly burned in 1894 and in 1955. A small
section was burned in 1974 (Stop 3).

The impact of burning on the present distribution and char-
acter of vegetation is difficult to assess. The openness of much
of the woodland south of Spot Pond may be attributable to fire,
as may be the dominance of red oak in that area. However, the
failure of seedling generation in the white pine stand at Stop 5
may be the product of infrequent burning and the consequent accum-

ulation of raw surface organic material.

Studies of unmanaged Connecticut woodlands indicate that disruption by fire may be only temporary. The forest in a burned area returned to its original character within 40 years of a major fire (Stephens and Waggoner, 1970).

The natural frequency   of fires in the conifer hardwood forest of New England is probably low. In conifer forests in Minnesota, distinctive fires occur about every 100 years, although species are differentially affected (Heinselman, 1973).

Windthrow by storms is a natural hazard in the woodlands of southern New England. The storms do substantial damage, but may also have an important role in the removal of old trees and the thinning out of stands. The frequency of widespread windthrow is small and largely confined to occasional hurricane storms. Although such storms occur about once a decade, widespread devastation happens only every 100-150 years (Gould, 1960). Destructive hurricanes were recorded in 1635, 1815, 1938, 1944, and 1954. The 1938 storms were the most severe of the recent hurricane storms. It did huge damage throughout the southern New England In the Fells, the Lawrence Woods and Spot Pond sections were the hardest hit. Windthrows were cleared, brush was burned. Not only were parts of the area unequally affected, but types of woodland were probably differentially damaged. White pine stands over 20-40 years old were particularly susceptible to blowdown. Hardwoods, however, were generally more resilient. Only stands over 60-80 years old were subject to massive blowdown (Gould, 1960).

The area has been severely damaged by gypsy moths. The inadvertant introduction of the moth into North America occurred in 1869, when moths escaped from a laboratory in nearby Myrtle Street, Medford (Hitchcock, 1971).

Chestnut, once an important component of most hardwood communities in southern New England, was eliminated in the early years of this century by chestnut blight disease.

Since 1894, and the creation of the reservation, many trees have been planted. Only a few general locations of the plantings are known. Some of the white pine and hemlock stands may have originated in this way. Their even age may be indicative of such an origin, although even-aged stands are very common in New England forests, and may be associated with fire, disease, windthrow, or lumbering.

Each of the forest communities in the Fells is composed of a small number of interrelated species that appear to reflect landscape position as well as the effects of the disturbances indicated above. Soil depth and soil moisture availability are critical variables. In the Fells, thin soils and dry soils are generally coincident. Aspect is locally important. South-facing slopes

tend to be drier than those facing north. Compositional variety (number of species) delines from moist, but well-drained sites to dry sites with thin soils and poorly-drained organics.

In the Pine Hill area, the lower, well-drained slopes have a diverse hardwood community dominated by red maple and red oak. The drier, thinly-covered ridges, have an open woodland of white pine and red oak . Red maple increases in importance in the wet locations.

In the Spot Pond section, the open area near Stops 2, 3, and 4 is dominated by red oak, but has a well-developed ground cover that includes blueberry, dogwood and sassafras.

The present woodlands are dominated by deciduous hardwoods, particularly red oak and red maple. The hardwoods have replaced the once-dominant conifers because of the ability to recover rapidly from disturbance. Red oak and red maple are particularly prolific root-sprouters. The conifers do not have this means of rapid regeneration.

Tree Rings

Tree ring data are useful in establishing age-size, and community structure-age relationships. Where trees are responsive to climatic variations, tree rings may be used in the reconstruction of past climates. An annual ring comprises a sequence from large diameter, thin-walled xylem cells produced in early spring and summer, to progressively smaller diameter cells with thicker walls produced in autumn. The abrupt change to the next year's early wood marks the ring boundary. Cell formation is dependent on the supply of photosynthate which is influenced by environmental conditions (Fritts, 1967). Sensitivity to climate is greatest where trees are in the open, and where stressful environmental conditions occur.

Tree rings from the Middlesex Fells area appear to be 'complacent' i.e., variation in ring width is conditioned by community structure rather than climate. A few examples are presented in Figure 4. No general trends are evident in the sample, except for the general outward narrowing of the rings, a function of age. Even trees of the same species share few similarities.

The patterns here probably represent variations in the supply of photosynthate that have been controlled by changes in community structure and composition. The tightly-packed rings of the hemlock (Fig. 4, #12) are probably due to intraspecific competition and to suppression as an understory component. However, the hemlock in the Pine Hill area are also understory, but show rapid growth in recent years (#4). Tree rings of hemlocks in New England purportedly show some coordination with summer rainfall (Lyons, 1943). Those in the study area show no common response.

A. Pine Hill area

B. Spot Pond area

diameter in inches
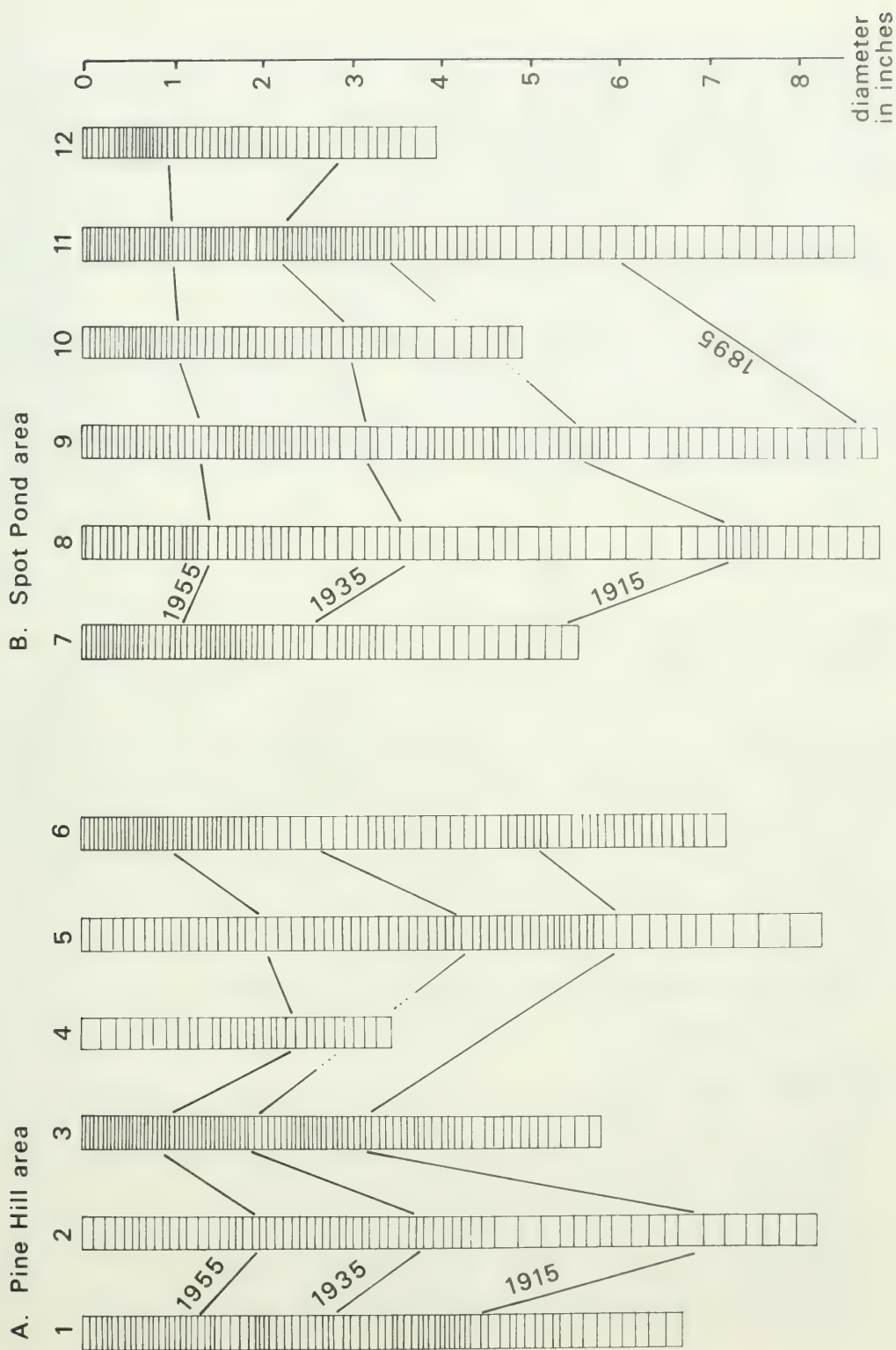
Fire and windthrow are important natural mechanisms in the modification of communities, although the effects of short duration disturbances are difficult to assess. Fire or windthrow should act to release understory elements and to stimulate surviving canopy trees by thinning out the woodland. These disturbances can be reflected in ring patterns.

Figure 4. Tree rings from canopy and understory trees in the Pine Hill and Spot Pond Areas.

1. Red oak (canopy, ridge top, dry site); 2. white pine (ridge top, dry site); 3. hickory (understory, moist site); 4. hemlock (understory, lower slope, moist); 5. red oak (canopy, lower slope moist); 6. red maple (canopy, lower slope, moist; 7. red pine (canopy, ridgetop, dry); 8. white pine (canopy, moist); 9. white oak (open woodland, moist); 10. red oak (open woodland, ridge top, dry); 11. red oak (canopy, moist); 12. hemlock (understory, moist).

Appendix

Common and Scientific Names of Species

Trees and Shrubs

white pine	- Pinus strobus
red pine	- Pinus resinosa
hemlock	- Tsuga canadensis
southern white cedar	- Chamaecyparis thyoides
eastern red cedar	- Juniperus virginiana
grey birch	- Betula populifolia
canoe birch	- Betula papyrifera
red oak	- Quercus alba
red maple	- Acer rubrum
chestnut	- Castenea dentata
dogwood	- Cornus spp.
sassafras	- Sassafras albidum
blueberry	- Vaccinium spp.
staghorn sumac	- Rhus Typhina

Herbaceous Species

sweet clover	- Melilotus alba
chicory	- Chichorium intybus
butter and eggs plant	- Linaria vulgaris
mullein	- Verbascum thapsus
dock	- Rumex spp.
goldenrod	- Solidago spp.
milkweed	- Ascelepius syriaca
ragweed	- Ambrosia spp.
pigweed	- Chenopoldium spp.

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Half-day Field Excursion to the Middlesex Fells.

Direction to the Fells (From Marsh Chapel, Boston University)

Turn right from Commonwealth onto University Road. Continue onto Storrow Drive and proceed eastward to rotary with signs for I-93 North. Join I-93 North and continue on it for approx. 5 miles. Take Route 28-Fellsway West exit. Circle rotary at exit for approx. 180°. Bear right at South Border Road sign. Follow road for approx. 350 yards to small unpaved parking area at Bellevue Pond.

Pine Hill Area:

Walk along path on east side of Bellevue Pond.

Mileage
  0.15 mile. Stop 1. Northeast side of Bellevue Pond.

The woodlands here contain the largest number of tree and
shrub species in the Fells. Red oak and red maple dominate the
canopy trees. Hickory, cherry, basswood and hemlock are impor-
tant understory elements. The diversity is partly a function of
soil moisture and aspect. The moist lower and middle slopes have
the greatest diversity. The upper slopes and ridge tops have few-
er species. Red oak and white pine dominate. Red maple increases
in importance in the wetter sites. The development of ground
plants and shrubs is largely dependent on the character of the
canopy layer. Where the canopy is closed, light intensities at
ground level may be small, sometimes less than 1% of above the
canopy. Closed canopy woodlands tend to have few ground plants
or contain species that bloom and set seed prior to the leafing
of the canopy trees.

Continue along path to:

  0.20 mile. Stop 2. Soil Profiles.

Soil exposures on both sides of the path. On the east side,
a thin soil appears to have developed from the underlying granod-
iorite boulders. Note the granular disintegration. The soil
exposed on the west side is typical of much of the Fells. The
thin stony soil is developed in glacial till. Stones occur throu-
ghout the profile which shows little variation in texture and no
distinctive horizonation. The Gloucester Series are acid soils,
partly because of the lack of bases in the parent material and
partly due to the removal of soluble minerals by percolating water.
Most of the nutrients in a forest ecosystem are being constantly
recycled within the biomass. Trees such as red oak and red maple
produce a litter layer that is quite acid and generally low in
potential nutrients.

Contrast and surface humus mat developed under deciduous
hardwoods at this site with that developed under conifers at Stops
1 and 5 in the Spot Pond area. Part of the difference can be
attributed to the character of the litter, but the greater accum-
ulation of litter under conifers results largely from the defi-
ciency of decomposer organisms and mixers.

Continue northward along path until its intersection with
path to Pine Hill (entering from right). Take Pine Hill path to
summit.

  0.45 miles. Stop 3. Pine Hill.

The limited vegetation cover over the upper parts of Pine Hill is related to the thin, dry soil, and extensive bedrock exposures, to disturbance caused by visitors to the site, and to occasional lightning strikes that cause localized burning.

Pine Hill Ridge is composed of light-colored Lynn Volcanics (Paleozoic) intruded by dark Triassic dikes. Note the effects of glacial scouring on the exposed bedrock at the summit. Some aligned grooves and striations indicate the direction of ice movement. Look around for erratics.

From the tower one can see the whole Boston Basin. The faultline scarp of the Northern Boundary Fault is still obvious to the east and west of the tower. Drumlins are prominent landforms throughout the city and as islands in the bay.

For further details of the geology of this area see Skehan, (1975)

Return down path to junction with main path continue north to clearing with rock piles to left of path.

0.80 miles. <u>Stop 4</u>. <u>Disturbed Area</u>.

The rock piles were dumped here during the widening of the off ramp from I-93 to Medford Square in 1971. The site has many weedy, 'disturbance' species that are well-adapted to the colonization of open spaces with little or no soil cover. They are typical of the early stages of plant succession, but are seldom found in the later stages because of their intolerance of shade and their inability to compete with perennial, woody plants.

The pioneer plants are mostly annuals and biennials. They grow rapidly and produce very large numbers of easily dispersed seeds. A large proportion of them have been naturalized from Europe. These exotics thrive in disturbed environments but seldom become community components in later stages of the succession. Herbaceous species at this site include sweet clover, chicory, butter and eggs plant, mullein and dock -- all exotics. Native species include goldenrods, and milkweed. Two of the most common disturbance plants ragweed and pigweed are not well-represented here.

Invasion by pioneer shrubs and trees are started. Staghorn sumac is prominent around the margins of the disturbed site. A few yound birch and poplar trees are noticeable.

Page and Weaver's "Wild Plants in the City" (see bibliography for full citation) is a well-illustrated guide to the vegetation of disturbed areas in Boston.

Walk west through the disturbed area. Turn south on path that climbs onto a ridge to Lynn Volcanics.

0.90 miles.   <u>Stop 5</u>.   <u>Thin Soil and Open Woodland</u>.

Ridgetops tend to have thin soil cover and many bedrock expo-
sures. The thin, dry soils generally do not support the same var-
iety and biomass as the wetter, deeper soils on middle and lower
slopes. Red oak and white pine dominate. In such locations,
closed canopy woodland seldom develops. The open character of
the ridge top woodlands is conducive to the development of an often
varied and continuous ground cover. Here that cover includes blue-
berry.

A similar situation is evident at Stops 3 and 6 in the Spot
Pond area.

Return to the car park at Bellevue Pond. Approx. 1.25 miles.

Return to rotary. Follow signs for Route 28 North (Fells-
way West). Note dikes in I-93 roadcut in side of Pine Hill. Turn
right at intersection with Elm Street. Continue along Elm Street
to rotary. Circle rotary (approx. 270º) to Woodland Road. Follow
Woodland Road for approx. 1/2 mile. Make turn at third left cut-
off. Park in small parking area on west side of Woodland Road.
(Figure 2).

Spot Pond Area

0.05 miles.   <u>Stop 1</u>.   <u>Hemlock stand on south side of path</u>.

This evenaged stand of hemlock shows considerable variation
in size, possibly related to soil moisture variations, but pro-
bably a function of community structure. The small hemlocks have
an oak overstory. These trees date from the 1920's, when many hem-
lock seedlings were planted in the Fells. Note the thick, raw
humus mat, and the charcoal fragments just below the surface.
Note the lack of seedlings from either the hemlock or the red oak.

Continue along the main path to intersection with short path
to edge of Spot Pond.

0.4 miles.   <u>Stop 2</u>.   <u>Spot Pond</u>.

Spot Pond is one of several lakes in the area that origin-
ate in hollows produced from ice scouring. It was enlarged last
century to accomodate ice houses, and later to increase its capa-
city as a reservoir.

Contrast the development of shrubs and ground plants in the
open woodland west of the path with the closed canopy pine stands
to the east. Sassafras and dogwood become important understory
shrubs in moist areas with an open canopy.

Return to the main path follow it for approx. 100 yards.
Branch left from path towards the low ridge to the south of the
park.

o.5 miles. Stop 3. Burned area.

   This area was burned over in the summer of 1974. The ground
cover was burned back, but mature trees were unaffected. Root
sprouts on red oak and red maple trees were burned, but sprouting
resumed the following year (1975). The importance of fire in
natural ecosystems is now being generally appreciated. Fire is
part of a natural recycling process that maintains maximum vigor
and diversity in most communities.

   Continue south along the ridge to large, perched boulder.

0.55 miles. Stop 4. Glacial erratic (?).

   This large boulder has obviously been moved from its origin-
al position. It may be considered as a large erratic. It is of
the same rock type as the underlying bedrock, and is unlikely to
have been transported very far.

   Descend to valley on the south side of the boulder. Walk
northeast (left) along gully. Climb up right side to a white
pine stand.

0.60 miles. Stop 5. White pine stand.

   White pine, like most pine species, appears to be fire-de-
pendent. Fire is necessary to remove excess surface litter and
to prepare the seedbed. Even pine seeds will not germinate in
thick acidic litter. Note the lack of seedlings in the stand.
White pine and hemlock were important elements in the regional
woodland at the time of settlement. Their demise can be partly
attributed to their removal for lumber, and is partly the result
of their inability to regenerate by root sprouting as do the
oaks and maples that largely replaced them.

   Note the thick, fire-resistant bark on the pines and the
lack of undergrowth. The soil is thin and acidic.

   Continue through stand to open woodland on ridge above the
stand (south-east).

0.62 miles. Stop 6. Open, ridge-top woodland.

   This area is similar to that at Stops 3 and 4, and that of
Stop 5 (Pine Hill area). The open woodland is dominated by red
oak. Red oak and red maple sprouts are common. White pine seed-
lings, probably from the nearby stand. The litter here is
thinner and less acid than under the pines. Moss can provide a
good seedbed for pine.

   Drop eastwards from the ridge to Quarter Mile Pond. Follow
shoreline northward.

0.75 miles.   Stop 7.   Contact between Precambrian granodiorite
and Triassic dike rock.

Note the textural differences and the baked contact.

Continue north to main path.   Turn right.   Return to Wood-
land Road parking lot.

STRATIGRAPHY AND FIELD ANALYSIS OF GLACIAL DEPOSITS NEAR WORCESTER,
MASSACHUSETTS[1]

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INTRODUCTION

Worcester lies at the eastern edge of the central Massachusetts
upland (Fig. 1), called the Worcester County Plateau by Emerson (1917), and
on the drainage divide between the southeast-flowing Blackstone River and
the northeast-flowing Nashua River. On this trip, we will discuss the
relationship of the major physiographic features to the distribution of
glacial deposits and the deglaciation history of the area, particularly the
southwest corner of the Nashua River lowland.

The main purpose of this trip is to illustrate techniques and concepts
used in making detailed surficial geologic maps. We will map an outwash
deposit (morphologic sequence) in detail, describe its morphology, clast
textures and lithologies, and depositional environments. We will then
relate inferred ice margin positions and local deglaciation events to the
regional late Quaternary history.

TILL STRATIGRAPHY

Alden (1924) followed Emerson's (1898, 1917) arguments when he dis-
cussed till in the Worcester area. Alden described a lower solid dark gray
till, and an overlying loose sandy grayish-buff till. He noted that the
contact between the two tills was gradational at all exposures that he saw,
and nowhere did the upper till appear to be a distinct deposit. At Stop 1
we will see the top 3 or 4 metres of the lower till at the top of a 20-metre
cut in a drumlin.

Richard Lougee (1957), professor of geomorphology at Clark University,
obtained a C^{14} date of >35,000 years from a peat bed beneath 20 metres of
lower till along the Massachusetts Turnpike in Millbury. Pollen in the
peat included oak, hickory, sweet gum, and very little pine, suggesting a
climate warmer than present in pre-lower till time.

Recent workers consider the lower and upper tills to be deposits of
two different ice sheets (Schafer and Hartshorn, 1965; Pessl, 1971; Koteff,
1970; Stone, 1975). The pervasive iron-manganese stain in lower till
matrix, dissolution of and iron stain around iron-bearing minerals, and
hydrated clay-sized illite are interpretted as products of subaerial
weathering, presumably at the base of a soil profile. The apparent trun-
cation and shearing of the top of the lower till, and the incorporation of
lower till clasts in nonoxidized upper till matrix suggests that the lower
till was deposited and weathered prior to the advance of the last ice sheet.

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[1]Publication approved by the Director, U. S. Geological Survey
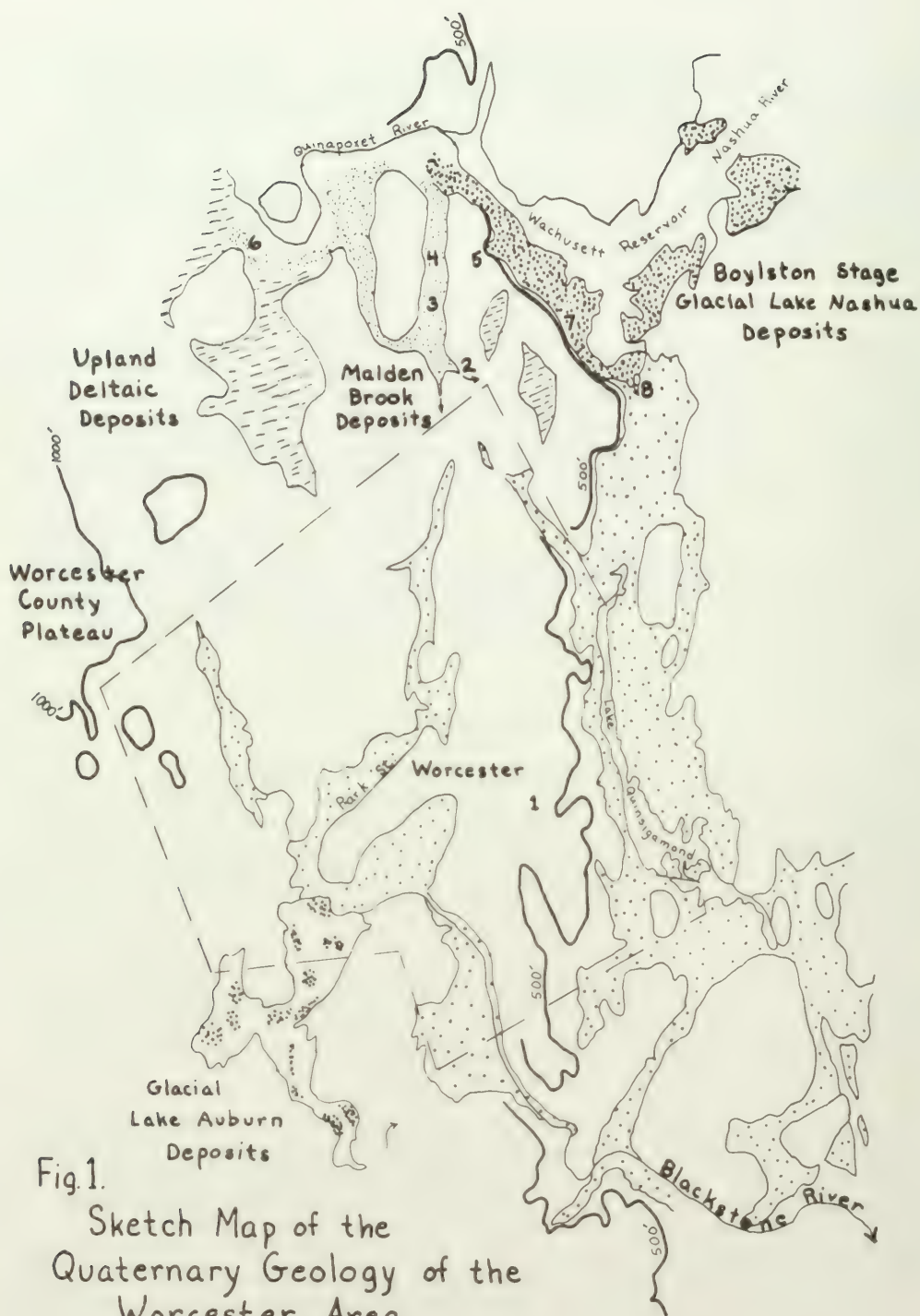
Fig. 1.

Sketch Map of the
Quaternary Geology of the
Worcester Area

Compiled from Alden (1924), and unpublished data of Lougee, Stone

0   1   2   3 miles

0 1 2 3 4 kilometres

176
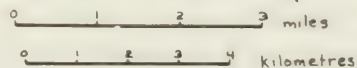
MELTWATER DEPOSITS

Details of the Quaternary geology and late-Wisconsinan meltwater deposits in the Worcester area have been described for more than 75 years. Crosby (1899a, 1899b) studied the area in connection with the building of dams for Wachusett Reservoir. He identified lake deltas and water levels of different stages of glacial Lake Nashua in the Nashua River lowland. We will see a good exposure of deltaic beds of the Boylston stage of Lake Nashua at Stop 7.

Alden (1924) published an excellent detailed surficial geologic map of central Massachusetts at a scale of 1:125,000. He showed the principal glaciofluvial valley deposits in Tatnuck, Beaver, and Quinsigamond valleys as terminal moraine deposits, a term in which he apparently included local sandy till and extensive collapsed sand and gravel. Alden described the Malden Brook deposits that we will map at Stops 2-4, as outwash sand and gravel. Alden attempted to trace stages of ice retreat in central Massachusetts, based on 15-minute maps of ice-contact deposits, and glacial lake deposits and their requisite retaining ice walls. His isochronal lines show development of a broad reentrant in the retreating ice front over the Worcester County Plateau, and adjacent broad ice-lobe fronts in the Connecticut and eastern Massachusetts lowlands.

Lougee and his students studied the glacial meltwater deposits of the Worcester area, but Lougee never published a formal report. In his class examples (provided by Bob Lingner, Worcester State College), Lougee illustrated the physiography of glacial Lake Auburn and associated deposits just south of Worcester. He outlined the stratigraphic relationships between the older Lake Auburn deposits, and lower (younger) fluvial valley train deposits in Tatnuck and Beaver Brook valleys (the Park Street valley train) to the north.

Recent 1:24,000-scale mapping in the Worcester North, Paxton, and Sterling quadrangles agrees with the conclusions of Crosby, Alden and Lougee. Glaciofluvial deposits in Tatnuck and Beaver Brook valleys in Worcester city are outwash systems graded to the major Blackstone River valley train. Deposits in the Quinsigamond valley to the east are fluvial sand and gravel in the upper 10 metres, on grade with the Blackstone valley surface. These fluvial beds overlie deltaic deposits in much of the basin which was glacially overdeepened below the fluvial base level. Detailed mapping near Holden, west of the Boylston stage Lake Nashua deltas, suggests a detailed local history of deglaciation. Several ice-marginal lakes, controlled by local bedrock spillways, are differentiated in the area previously mapped by Alden as general Quinapoxet stage Lake Nashua deposits. Ice contacts and inferred stagnant ice zone margins associated with these morphologic sequences indicate a northwest trend of the retreating ice sheet. The inferred local direction of ice retreat to the north-northeast is demonstrated in the very local deglaciation events that we will examine at Stops 2-7.

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SCALE 1:24 000

CONTOUR INTERVAL 10 FEET

FIG. 2. Base map of Malden Brook area.

ROAD LOG

Starting point is Crow Hill, Bloomingdale section of Worcester, east end of Clarendon Street (SE 1/9 Worcester North quadrangle).

FROM THE EAST: Mass. Pike to Millbury (Rte. 122) Exit; take Rte. 122 N and W into Worcester city; Puritan Ave., turn right (N) and proceed 3 blocks N; Hamilton St., turn left (W) and proceed 1 block; Pilgrim Ave., turn right (N) and proceed 3 blocks N; Clarendon St., turn right, and proceed to end of street, park on left.

FROM THE WEST: Mass. Pike to I-290 N; follow I-290 N to Rte 122 E (Millbury) Exit, exit right, and follow Grafton St. (Rte. 122) E; Billings Square, bear left onto Hamilton St. and continue E; Pilgrim Ave., turn left (N) and proceed 3 blocks; Clarendon St., turn right (E) and go to end of street, park on left.

Milage

0.0 STOP 1: Crow Hill drumlin, Beauregard and Boucher brickyard. The top 3-4 metres of lower till (drumlin till, old till) are oxidized and exhibit excellent subhorizontal fissility. The high proportion of striated phyllite clasts suggests high clay content of the till, hence suitability for brick manufacture. Sandy upper till (Wisconsinan) is virtually absent.
Leave Crow Hill headed W on Clarendon.

0.1 Pilgrim Ave., turn left (S)

0.3 Hamilton St., turn right (W)

0.6 Billings Square, join Grafton St. (Rte. 122), continue W

1.0 I-290 North, enter right, head N

3.0 Rte. 12 (Holden, Fitchburg) Exit right, and bear left toward Rte 12 North

3.9 Rte. 12, Boylston St., turn right (N)

7.2 Danielian Drive, turn left (W)

7.4 Woodland St., turn left (W)
park on right side of road
STOP 2: Upper Gates Brook. Flat and collapsed glacial outwash topography under the 550-560' surfaces in Malden Brook valley to the north indicates a local base level for these deposits in the narrow Gates Brook valley. Walk up Gates Brook, noting on your map (Fig. 2): bedrock outcrops, stream alluvium, till-outwash contacts, and outwash textures.
Leave Gates Brook headed W on Woodland St.

8.0 Prospect St., turn right (N)

9.1 Lee St., turn left (W)

9.2 Park on right side of road
     STOP 3: Lee St., Malden Brook deposits. Continue to map till-outwash
     contact on the E side of the valley, using the break in slope. You will
     see a good morphologic contact across the field to the N, at the base of
     the orchard behind the farmhouse. Observe stratigraphic, textural, and
     structural features in a small pit beside the pumping station. Walk N
     on collapsed ice channel topography and observe coarse textures in the
     small pit in the pasture to the N. DO NOT CLIMB THE FENCE. Return to
     Lee St. and walk NW. Map the till-outwash break in slope on the W side
     of the valley.
     Leave Stop 3 headed NW on Lee St.

9.8 Goodale St., turn right (NE)

10.4 Gravel pit, enter right
     STOP 4: Goodale St. head of Malden Brook outwash. Note stratigraphic,
     textural, and structural features in pit face. Continue to map till-
     outwash contact in the woods to the SW, and N of Goodale St. Time per-
     mitting, we will walk NE on Goodale St. to map the outwash. Sketch a
     longitudinal projected profile of the maximum elevations of the Malden
     Brook deposits on the graph in Fig. 2.

11.2 Newton St., turn right (SE)

11.5 Prospect St., turn right (S)

11.6 Park on right side of road.
     STOP 5: Meltwater channels - spillways. Walk west up the meltwater-
     carved channel cut in till, and return to Prospect St. Relate outwash
     deposits and ice margin positions in Malden Brook valley to these channels.
     Cobble gravel of Boylston stage Lake Nashua delta underlies the flat
     field to the E of Prospect St. The gravel appears not to have been
     eroded by the meltwater that eroded the channels to the W, suggesting
     a local chronology of events in both Malden and Nashua River valleys.
     Turn around and head N on Prospect St.

11.7 Newton St., turn left (W)

12.0 Goodale St., turn left (W)

13.4 Malden St., bear right, continue W

14.6 Bear right at road junction

14.9 Harris St., turn left (SW)

15.3 Wachusett St., turn right (N)

15.6   Sand and gravel pit, enter left
        STOP 6: Holden sand and gravel: Ice-contact delta graded to Gates
        Brook spillway. Observe a good variety of primary sedimentary structures
        and penecontemporaneous deformation structures.
        Leave pit headed E on Wachusett St.

        Retrace route on Wachusett, Harris, Malden, Goodale and Newton Streets

19.5   Prospect St., continue E on Newton

19.7   Join Central St. in village of West Boylston, continue SE on Rte 140.
        Continue to map 500' contour break in slope contact of delta fluvial
        topsets with gentle till slope. Note ice contact slope (inferred ice
        margin position) on left side of Rte. 140 after crossing railroad tracks.

21.2   West Boylston land-fill, enter right
        STOP 7: Delta, Boylston stage glacial Lake Nashua. Compare strati-
        graphic, textural, and structural features with those at Stop 6.
        Leave land-fill headed SE on Rte. 140.

22.6   Park on right side of road, well off busy road.
        STOP 8: Spillway of Boylston stage glacial Lake Nashua. Walk into
        saddle in woods just south of Rte 140, elevation 445'. Note bedrock
        floor of spillway, and lake sand just north of spillway lip.

        Leave spillway headed E on Rte. 140

        TO GO TO BOSTON: Follow Rte. 140 to I-290 EAST, to I-495 SOUTH, to
                          Mass. Pike
        TO GO WEST: Follow Rte. 140 to I-290 WEST through Worcester, to Mass.
                  Pike.

Trip A-7

GLACIAL GEOLOGY OF SOUTHEASTERN MASSACHUSETTS

by

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Introduction

By the time the retreating late Wisconsinan glacier began to uncover the area northwest of Buzzards Bay, it had melted down to a surface that resembled a small-scale combination of karst and a mature stream-carved landscape of debris-covered ice with relief of several hundred feet. Along the irregular front, meltwater streams poured from subglacial tunnels or through superglacial valleys carved in the ice, leaving as legacies the proglacial outwash plains and the many forms of ice-channel fillings. In long openings between the rapidly melting ice and low till hills or drumlins, the streams laid down ponded and fluvial deposits that were to become kame terraces as the glacier finally melted away. Further back, large depressions in the ice were occupied by through-flowing streams or by impounded water bodies, thus producing kames of many shapes that rise above today's landscape and that show either stream or quiet-water deposits. By the time the large proglacial lake that occupied the lowest land drained away, the glacier had melted completely away from the area we are interested in and the geologic agent that took over was the wind. It picked up the fine-grained portion of newly exposed till and outwash and deposited a layer of silty sand that overlies nearly all of the glacial features in the landscape and is commonly filled with wind-carved pebbles. This eolian mantle, called loam, is what enables the New England farmer to survive on the otherwise infertile stony sandy till or the sterile pebbly and cobbly outwash bodies.

The Field Trip

The constant change brought about by the demand for sand and gravel as construction material, as landfill around building sites, and as cover in large sanitary landfills means that it is impossible to set up an itinerary in the spring and see the same features at the scheduled stops on the itinerary in October. Indeed, new environmental regulations mean that more gravel pits are now being graded and covered, removing some outcrops completely. Thus, this field trip will have no published itinerary in the Guidebook. Instead, a general description of the landforms we will see (they can't disappear entirely) and the glacial features of the area will give the setting for the field trip. A final itinerary, map, and road log will be distributed on the field trip.

<center>Glacial Geology</center>

The physiographic setting of the glacial geology is the Narragansett Basin and the granitic low areas south of the Basin. Total relief in the area is generally low, and hills that rise more than one hundred feet above their base are uncommon. Thus, the glacial geologist looks for scarps that may be less than 10 feet high, or kames that rise 20 feet above the surrounding area, or deltas that may be as little as 15 feet above the lake bottom (Hartshorn, 1960 , 1967).

The till that is the substrate on which all other glacial features are formed and from which the stratified glacial sediments were derived is greatly influenced by the bedrock in the area. The Dedham Granodiorite is a light-colored granodiorite to quartz monzonite and contains quartz, microcline, plagioclase, and biotite (Koteff, 1964). The Rhode Island Formation is a light- to medium-gray sandstone, siltstone, and conglomerate with quartz, sericitized clay minerals, and feldspar. These rocks, and a few other varieties, generally produce a light- to medium-gray till, although other shades of gray, pale yellowish brown, or similar light colors can also be found. The till, a mixture of grain sizes ranging from clay through boulders as much as 20 feet in diameter, is commonly sandy, loose, and very stony. Outcrops at which to see a good till section are nearly non-existent, for till has little market value and is generally not quarried.

A particular kind of till, derived entirely from superglacial debris, can be found in many of the ice-contact features, particularly in kames, kame terraces, and ice-channel fillings. This flowtill (Hartshorn, 1958) occurs as lenses or beds of till a few feet thick that flowed as a muddy watersoaked mass from surrounding glacial hills onto sediments in the glacier's topographic lows. The composition of the flowtill differs from the till generally mapped as ground moraine, because the farthest travelled rocks, from north of the Basin, tend to be concentrated on the surface of the ice as it melts away and so the flowtill contains more non-Basin rocks than the subglacial till that makes up the general till blanket on bedrock. The flowtill is easily recognized in the various ice-contact features, for it is commonly interbedded with the sand and gravel or forms the last episode in the buildup of the deposit and hence is the uppermost sediment in the landform.

As shown by the flowtill, the surface of the glacier was partly covered with superglacial debris picked up from the ground just to the north and carried to higher altitudes in the ice by glacier shear or by streams flowing under hydrostatic head and emerging as fountains or from tunnels a few hundred feet above the base of the ice.

As the margin of the ice thinned, it developed an irregular surface characterized by hills of ice with some superglacial debris cover and by depressions that ranged from sinkholes only a few tens of feet in diameter to larger depressions and integrated valleys carrying large meltwater streams and mantled with stratified debris tens of feet thick. This ice topography was first formed many hundreds of feet above the bedrock or till-covered floor under the glacier. As the glacier melted further, the ice topography constantly changed as hills lost their protective cover of debris, melted away, and became hollows, and as former low areas with their deposits of sediments resisted melting and became

<center>184</center>

temporary hills. Only when the underlying ice was nearly gone would the first
of the ice-contact deposits be p reserved; some would be let down the last few
feet and would contain some disturbed beds, others would be formed on the
ground and would show disturbance only at the margins.

The numerous hummocks, hillocks, mounds, mesas, hills, or flat tablelands
made of stratified debris are arbitrarily divided into landform classifica-
tions - kame, kame terrace, kame plain, esker or ice-channel filling, outwash
plain, and undifferentiated stratified drift. Reconstruction of the original
landform shows that t he present form is a result of the positioning of rem-
nant blocks and masses of ice during deglaciation and not the result of
different processes. The average grain size of many landforms, so differently
named but closely related in space, may turn out to be nearly similar, as may
the internal structure. On the other hand, it is clear that not all kames
or kame terraces, for instance, were formed the same way. Some, which consist
of stream gravels from bottom to top, show that streams poured through the
depressions in the ice. Others show evidence of deposition in standing water,
either by deltaic foresets and topsets or by the characteristic structures
and fine-grained texture of the sediments. Thus the map units are not
inflexibly defined, and discussions of the glacial history need not be limi-
ted by landform names on the surficial map.

Evidence of ice-marginal positions is common, though not in the form of
moraines, as is usual in the Midwest. Moraines are rare, linear kames or
lines of kames are more common but their origin and meaning are a puzzle,
a few lines of kame deltas are known, and heads of outwash are most common.

An end moraine composed of a line of irregular hills as much as 100 feet
high, trending east-west, has been mapped south of Great Quittacas Pond. The
end moraine contains sand and gravel, but no till, and is thought to be a push
moraine formed by a minor readvance of the glacier over previously deposited
glaciofluvial sediments (Koteff, 1964). A kame in Berkley, about 2400 feet
long in an east-west direction, about 900 feet wide, and about 85 feet high,
shows evidence of either minor readvance of the glacier or most unusual
slump deformation. Here beds of varved sand and clay form an anticline and
other beds are found vertical positions with apparent shear zones cutting
off the upper parts of the beds. No till is found overlying the contorted
sediments.

Other forms of glacial deposits can be used to infer temporary stopping
places for the ice margin. Perhaps the most striking feature, one which
allows the geologist to separate out minor phases in the deglacial history,
is the head of outwash -- a northerly facing ice-contact slope that marks
either a temporary halt in the retreat of the ice margin, a place where a
large block of ice remained for some time, or a place where deposition was
so swift and overwhelming for a short period before the stream was diverted
elsewhere or stopped flowing that it gives the impression of a halt in the
ice-marginal retreat. Many such heads of outwash can be seen in southeastern
Massachusetts; usually they are more clearly visible on topographic maps than
in the field because of heavy forest cover. They are commonly characterized
by low-lying swamps or outwash to the north, a scarp of from 10 to 100 feet
high whose outline is scalloped, digitate, or broadly irregular, the presence
of kettles and hummocky topography near the scarp or on it, isolated kames
north of the scarp, ice-channel filings trending into the scarp, and a broad,
moderately smooth fluvial plain trending away from the scarp. The glacio-

fluvial plain, commonly broken by kettle holes and large depressions into a series of kames and kame plains, declines gently in a southerly direction and may abut against yet another ice-contact scarp to the south.

At the same time, and ranging over a span of time from when the glacier was still thick and perhaps still actively advancing to very late in the glacial history, ice-channel fillings or eskers were forming. Glacial streams, flowing on the subglacial floor or just above the floor in ice tunnels, aggraded their channels to a depth of several tens of feet. These early subglacial forms are difficult to distinguish from similar linear ridges that were formed in ice-walled valleys open to the sky, except that where lenses of flowtill are present in or on the ice-channel filling it may be inferred that a valley slope existed down which the till moved, for there is little chance of masses of till falling from subglacial tunnels into the stream channel.

As the ice margin retreated to the north and northwest, it became more nearly a straight, solid glacier front where it ended in standing water. In some places the topography forced the meltwater to become ponded in large proglacial lakes instead of flowing directly away from the ice as proglacial streams. Where this occurred, low-lying areas were filled with as much as 100 feet of lake sediments, commonly varved clay, and the temporary northern shores of these lakes were formed of rows of kame deltas that trend east-northeast. These kame deltas are commonly very well developed, with free-standing frontal slopes, an ice-contact slope at the rear, and a clear indication of the water level, either from the intersection of topset-foreset beds or from the break in slope at the front of the delta. Many of the larger flat-topped bodies of stratified drift seen in southeast Massachusetts are deltas, but the first of a series of clearly defined deltas in irregular rows starts with the Pine Swamp delta near Taunton and the line of deltas with a water level of about 65 feet altitude extending eastward from Bridgewater. The last line north of this row includes the deltas along Route 106 south of Brockton, which stretch east-northeast for 7 1/2 miles.

In front of most of these deltas, and irregularly interspersed between them, are the deposits of varved clay. Estimates of the length of time that the largest water body remained in existence are from at least 100 years (Antevs, 1928) to 250 years (Hartshorn, 1960).

The northern margins of the lakes, where not marked by kame deltas, cannot be distinguished except perhaps by the boundaries of low-lying areas of fine-grained sediment such as clay, silt, or very fine sand. The now-vanished ice front was the margin elsewhere, and it is generally not possible to reconstruct that front except at the kame deltas. The non-glacier perimeters of the lakes likewise are difficult to delineate. The margins seem to have been a combination of higher topography, mostly till hills, higher heads of proglacial glaciofluvial bodies, and detached remnants of ice, some of which were wholly or partly buried by sediment.

The lakes were nearly the last of the direct glacial landforms to be deposited in any area. When the lakes drained, the proglacial meltwaters spread outwash over the lower parts of the lake bottoms and quickly became established in streams that are the direct ancestors of the larger streams in the area today.

The eolian mantle is a layer of silty sand to sand found nearly everywhere in the area, which contains windcut stones, or ventifacts, from bottom to top and hence must have been deposited primarily by the wind. The rocks of southeastern Massachusetts seem to make good ventifacts and both the topography and the early postglacial climate must have been conducive to wind work, for it is difficult to see a section without the eolian mantle, or the eolian mantle without several dozen ventifacts. The granitic and volcanic rocks more readily take a cellophanelike polish and are best fluted and pitted by wind abrasion because of their composition and texture. Very few ventifacts have the classic faceted form of the Dreikanter; most are merely polished and etched on one or more sides. The eolian mantle is mostly mixed with the underlying glacial deposits and hence partakes of the stoniness of those materials.

The last geologic agent to affect the area is humanity. Bulldozers for moving sand and gravel, dynamite for blasting rocks, and the construction of homes, sanitary landfills, school complexes, highways, and cities change the landscape as surely as any "natural" agent. No quotation marks are needed – all humanity acts as a geologic force, and here in southeastern New England the glacial geologist who has a special interest in the landforms can see them change, diminish, and disappear over a few decades.

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Probable 1:24,000 Topographic Quadrangle Maps

Assawompsett Pond
Assonet
Bridgewater
Brockton
Fall River East
New Bedford North
Taunton
Whitman

SEDIMENTARY AND GEOMORPHIC ORIGIN AND
DEVELOPMENT OF PLUM ISLAND, MASSACHUSETTS:
AN EXAMPLE OF A BARRIER ISLAND SYSTEM

by

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Boston University   Department of Geology
                                                   Boston University

INTRODUCTION

The origin and development of barrier islands has received much attention
over the last decade as geologists and geographers have become more concerned
with man's coastal environments (e.g., Hoyt, 1967; Fisher, 1968; Dolan, 1973;
Schwartz, 1973). This field trip and guide will examine many of the geomorphic,
sedimentary and vegetational features of Plum Island, Massachusetts, which ex-
emplifies a coastal barrier system.

Plum Island is 8 miles long and varies from 1/4 to 1 mile in width (Fig. 1).
It is composed mainly of well-sorted beach and dune sands and marsh deposits.
Glacial till, outwash and marine clays are also present at its southern end
(Nichols, 1964, p. 32; Sammel, 1963). Some of the features of this island are
formed by daily low energy conditions that can usually be observed on a field trip
while others are formed during high energy storms. The latter retain their
characteristics during the more prevalent lower energy conditions.

Plum Island also represents the dramatic differences which exist between
the altered and the natural sections of a barrier environment. These differences
will become apparent when the altered northern end of the island is contrasted
with the unaltered Parker River National Wildlife Refuge at the southern section
of the island. Dolan (1973) made similar observations and comparisons between
altered and natural barrier island systems along the North Carolina coast. An
active surf zone will be found along the Plum Island shoreline. As waves break
along this shoreline, sediment movement can be observed within the swash zone.
In the northern, altered section, a steep-sloped, coarse sediment-bearing, high
energy littoral zone may be contrasted with the natural beach of the southern
section which is gently sloped, less energetic, and composed of finer grained
sands.

A well-defined berm is developed in the refuge, and the backshore slopes
from this berm into the foredunes. The development of foredunes is believed to
be related to the migration of sand accumulation in the backshore area caused by
wind action (King, 1973). When these dunes reach a zone of less active energy,
pioneer plants may become established and stabilize the foredunal area (Godfrey
and Godfrey, 1973). The entire dunal field is an area of less active energy
(Coastal Research Group, 1969; Jones, 1974). Many plant species are capable of
existing and establishing themselves in a dunal area (Brown, 1959; Jerome and

FIGURE I
PLUM ISLAND
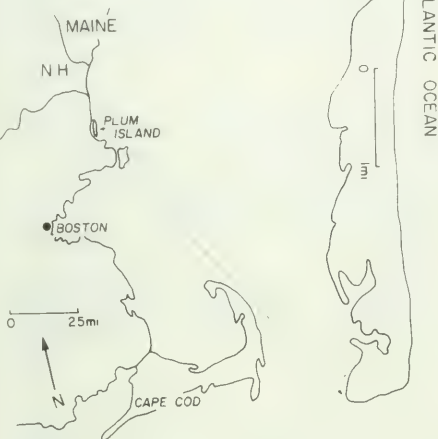
PLUM ISLAND CROSS SECTION[1]

ATLANTIC OCEAN

MAINE

N H

PLUM
ISLAND

●BOSTON

0   25mi

N

CAPE COD
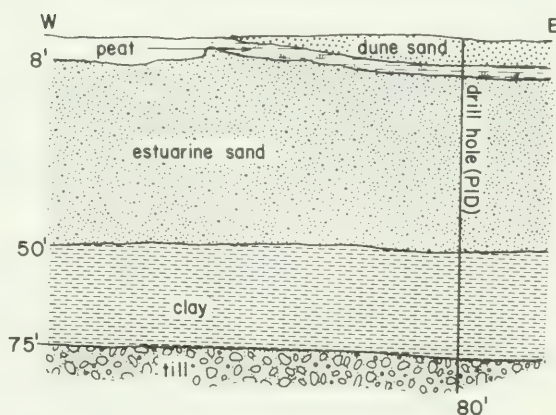
Figure 2.   East-west cross-sectional inter-
pretation of southern Plum Island, as pro-
posed by Rhodes (1973).

Figure 1.   Location map of Plum Island.

ORIGIN OF PLUM ISLAND[1]
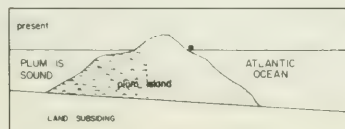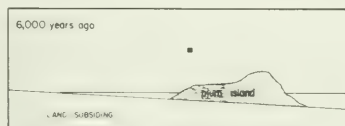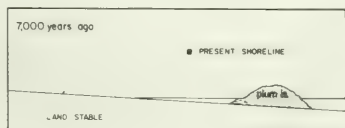
Figure 3.   Origin of Plum Island as proposed
by McIntire and Morgan (1963).   They hypoth-
esized that the rise in sea level appears to
have been greater than glacial rebound for
this area 7000 years B. P.   The beach ridge
(Plum Island) was encroached by the ocean
until an equilibrium was reached about 3000
years B. P.   Plum Island then developed
southward through longshore sediment trans-
port processes.

[1]MODIFIED FROM McINTIRE and MORGAN, 1963

others, 1968). When this particular vegetation becomes established, the dunes then become stabilized (Godfrey and Godfrey, 1973; McCann and Bryant, 1972).

The landward (west) side of the island is a "salt marsh" protected by the dunal system. It is normally not affected by high energy conditions, but some storms do cause flooding in the marsh and adjacent mainland areas.

FORMATION OF PLUM ISLAND

Plum Island began forming at least 6,200 years ago according to Carbon-14 dating of marsh peat (McIntire and Morgan, 1963). The surficial sediments of Plum Island are unconsolidated sands with some transported glacial till found at the southern end (McIntire and Morgan, 1963; Sammel, 1963; Nichols, 1964; Coastal Research Group, 1969; Rhodes, 1973), primarily in the form of drumlins.

According to Clapp (1921) the underlying bedrock for the Plum Island barrier system is Paleozoic metamorphosed igneous and sedimentary rocks and unaltered igneous rocks. See Rhodes (1973) for a study of bedrock profiles, mainly across Castle Neck to the south (Fig. 2).

McIntire and Morgan (1963) postulated that the local sea level is presently higher than during the early development of Plum Island 10,000 to 11,000 years ago at the end of the Wisconsin Glaciation (Fig. 3). With the retreat of this last continental glacier, vast amounts of water and sediment were released and transported to the sea by fluvial processes. According to their theory, the deposition of sediment was greater than the subsequent rise in sea level, thereby forming an offshore bar. The land was also rebounding because of the ice retreat which appears to contribute to the gentle slope needed to form an offshore bar-barrier island complex (Hoyt, 1967).

The fresh water swamp area adjacent to the mainland was encroached by the transgressing sea, eventually forming a salt marsh. This encroachment has been documented by McIntire and Morgan (1963) through Carbon-14 dating of the fresh water and salt marsh peats, by McCormick (1969) through analysis of cores and by Rhodes (1973) through wash-bore sampling and seismic refraction.

About 3,400 years ago sea level at Plum Island reached a standstill, but the offshore bar-barrier island continued to increase in size. The offshore barrier island complex then became attached to a drumlin, which is now the southern end of the island (McIntire and Morgan, 1963). Today, sea level at Plum Island is approximately at the same level it was 2,000 years ago (McIntire and Morgan, 1963).

Rhodes (1973, p. 30-31) found a layer of peat beneath the surficial dune sand which he thought represented a pre-dune marsh associated with a lower sea level (Fig. 2). This supports the theory of dune sand migration over marsh (peat). Rhodes (p. 58) considered that when the sea level rise tapered off to the present 0.3 feet/century the migrating barrier island became anchored to drumlins. He also found bedrock highs under Plum Island and Castle Neck (Rhodes, 1973, p. 38). He (p. 55) concluded that his findings gave "...all major barrier-island theories some support ...," including (1) littoral transport (Dana, 1894;

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Gilbert, 1890), (2) spit development through waves cutting drumlins (Johnson, 1925; Nichols, 1942; Fisher, 1968), and (3) relict beach ridges (Hoyt, 1967).

A new mechanism of barrier island migration was proposed by Jones (1974, p. 1), who "...hypothesized that a migrating dunal system rather than transgressive sea level changes at Plum Island, Massachusetts, is the current cause of this barrier island system migration." This new mechanism coupled with longshore drift was suggested by Jones and Cameron (1975) as the controlling mechanisms for the formation and present-day landward (westward) migration of the Plum Island barrier island system.

ACKNOWLEDGEMENTS

STOP DESCRIPTIONS

Stop 1. Merrimack River estuary (Fig. 4) – The Merrimack River, which is the fourth largest in New England, has a drainage basin of over 5,000 square miles and is one of the two sources of sediment for the Plum Island system (Coastal Research Group, 1969). The U. S. Geological Survey (1968) found the average daily discharge of the river to be about 7,000 cfs. and the amount of transported sediment to range from 2,860 tons in April to 46 tons in September for 1967. Much of this sediment is deposited on the Joppa Flats section of the estuary (Hartwell and Hayes, 1969) along the immediate shoreline. Recent dredging operations indicate that some of this transported sediment is also deposited in the river channel. These flats were once an area of high soft-shell clam productivity but pollution has closed this area to shellfish digging (Jerome and others, 1965).

The total estuarine area at mean high water is almost 4,000 acres of which 46.7% is intertidal marsh. An additional 2,300 acres of rarely submerged marsh also drain into the Merrimack River estuary (Jerome and others, 1965). This estuary acts as a buffer zone between Plum Island and the mainland because a tidal marsh absorbs excess water during storm conditions (Burton and others, 1965). This absorption process prevents many floods from reaching the lowlying

Figure 4. Merrimack River Estuary, a major sediment source
for Plum Island. Joppa Flats are viewed at Stop 1.

GENERALIZED DUNE VEGETATION TRAVERSE AT PLUM ISLAND
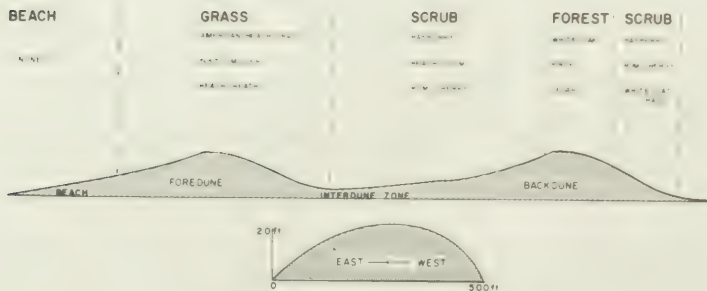
Figure 5. Generalized dune traverse noting major
vegetative zones (viewed looking southward).

coastal towns. The estuary also provides nursery grounds for the many an-
adromous finfish inhabiting the North Atlantic (Jerome and others, 1965;
1968).

Stop 2. The South Jetty Area - The north end of Plum Island exhibits
the greatest amount of shoreline change during the past 150 years (Chute and
Nichols, 1941; Nichols, 1942, 1964). The development of this northern section
is closely related to the offshore bottom topography and dependent on storms
(Hayes and Boothroyd, 1969).

The predominant direction of the storm waves is from the northeast, but
according to Hayes and Boothroyd (1969) the offshore bottom topography,
which consists of a series of sand bars, causes these northeast storm waves
to refract so that they then approach from the southeast. This refraction
process produces erosion at areas not protected by the jetties or groins. A
view of this refraction process can usually be seen off the south jetty.

This northern tip suffered severe erosion in February, 1969, and again
during many storms in 1972. The February, 1969, storm caused a loss of over
200 feet of shore-front property along this beach. The effects of the storms
on the northern section of Plum Island caused the Army Corps of Engineers to
declare this area a "critical erosion zone" in 1971.

Evidence of these high energy conditions is seen in the dunal bedding along
this beach. There are two distinct layers of sediment present: a fine-grained
layer of quartz sand and a coarse layer composed of coarse quartz sand and clam
shell fragments. The vegetation fronting these foredunes is sparse and the
dunes are not stabilized. The absence of vegetative cover is related to the
high energy conditions present at the northern end of Plum Island (Jerome and
others, 1968). Some vegetation is established behind this frontal dune and
this appears to be related to the lower energy conditions found in the area ad-
jacent to the Coast Guard Station.

Historically, this part of Plum Island has been subject to dramatic shore-
line changes. It has been suggested by Hayes and Boothroyd (1969) that this
area will continue to erode, and it appears there is very little man can do to
prevent this erosional process from occurring.

Stop 3. Plum Island Center - Plum Island Center beach is another location
which is a "critical erosion zone" (U. S. Army Corps of Engineers, 1971).
This area is densely populated in contrast to northern Plum Island which is
primarily non-residential government land.

Storms that buffet this area not only remove sediment, but destroy many
homes on the upper beach face. The February, 1969, storm undercut this upper
shoreline, causing cottages to topple downward onto the beach. A storm in
February, 1972, which caused widespread coastal damage in Massachusetts, also
caused heavy losses to cottages and property at Plum Island Center (Jones, per-
sonal observations, 1972).

As a result of these high energy storm conditions, Plum Island Center beach
exhibits well-developed erosional features. The slope along this beach is the
steepest found at Plum Island (Coastal Research Group, 1969). The average sedi-
ment size is large and most sand deposition occurs on the south side of the

groin due to storm wave refraction. There are also many beach cusps visible at this stop.

The Commonwealth of Massachusetts and the Town of Newbury in conjunction with the Federal Government have replenished the sand at this site during the last few years. This replenished sediment is distinguished from the indigenous sand by its textural characteristics, e.g., its larger size. However, immediately north and south of this location, the natural sand is coarser than along the far southern end of Plum Island because of the higher energy erosional and sorting conditions along the northern end.

In North Carolina beach replenishment projects and other stabilization attemps are more erosionally detrimental to a barrier environment than allowing the natural wave overwash process to occur (Dolan, 1973). It would then seem likely, from the conclusions of Dolan's study (1973), that the beach replenishment project at Plum Island Center beach will only contribute to erosion, will continue to need seasonal sand refill, and, due to the resultant higher energy conditions, will introduce coarser sand into the system.

Stop 4. Low Energy Beach - The beaches along the shoreline of the Wildlife Refuge differ dramatically from the northern beaches. When a southern beach is contrasted with a northern beach, the southern beach exhibits a lower beach slope, smaller sediment size and the development of accretionary features. Beach profiling also shows that these southern beaches restore their equilibrium slope more rapidly after storm conditions (Coastal Research Group, 1969).

The most common accretionary features seen along the shoreline are ridges and runnels. King (1973) concluded that their development on a low energy beach indicates progradation or non-erosion.

This low energy beach also exhibits a well-developed foredune. The sediment size at this location becomes progressively smaller from the beach to the foredune environment (Anan, 1969; Jones, 1974). Some of these dune segments are well stabilized by American beach grass (Ammophila breviligulata). The complex root system of the dune vegetation is exposed in cross-sections of some dunes. These dune grasses represent the pioneer plants in the vegetative succession on a barrier island. These grasses are highly adaptive and exhibit a high salt tolerance. They are also capable of storing moisture which rapidly percolates downwards through the porous dunes (Jerome and others, 1968).

Contrary to other coastal areas along the Atlantic coast, there has not been an attempt to artificially stabilize these dunes with exotic grasses. Time has proven that stabilization attempts by man can be more harmful to the system than allowing natural processes to take place (Dolan, 1973; Godfrey and Godfrey, 1973). Man's absence from the southern part of Plum Island has an advantage in that protection for his structures is not necessary. (For example, compare this location to that of Stop no. 3.) The foredunes act as a buffer between the surge waves and the area behind the dunes. According to Dolan (1973, p. 263):

> Natural barrier islands are much better adapted to steady-state processes and extreme events than are the man-manipulated islands. Since there is little resistance to the storm surge movement across the natural barriers, wave energy is dissipated across

the wide berm, among the low dunes, and finally in the grasslands and marshes behind. These islands actually gain material from the beach as the surge moves across the islands, and such deposits serve as sources of supply for new dune growth.

Although the southern end generally does not exhibit erosional features, high energy winds do, sometimes, breech the foredune barrier causing blow-outs, but rapid re-adjustment usually takes place. Blow-outs are caused by unusually high winds. It is not uncommon to experience wind speeds exceeding 50 mph along the Plum Island Shoreline (Coastal Research Group, 1969; Jones, personal observations, 1972).

Stop 5. Kettle Hole Nature Trail - This area is not a glacial feature. Its "kettle-like" form in the dunes has been designated a self-guiding nature trail. This site was selected as a stop because it exhibits the adaptability of dunal vegetation to adverse factors. The sediment is very fine throughout this area and continues to become fine southward along the dunal belt (Coastal Research Group, 1969; Jones, 1974). The presence of garnet might suggest a northern New Hampshire-Maine source for the sand.

Vegetation appears to be the greatest stabilizing control of the dunes, especially due to its entrapping root system. There are many vegetative species represented in this depression. The height of the trees does not exceed the rim of the "kettle". This tree height shows the relatively low salt spray tolerance of the tree species found in this coastal environment (Brown, 1959). An idealized example of vegetative succession for Plum Island is illustrated in Figure 5.

Examples of sand encroachment are seen on the frontal kettle dunes. The fine sand has been moved by the wind, so that now the trees are surrounded by it. An example of a blow-out where vegetation is sparse can be seen northeastwardly from the crest of the dune. This naturally stabilized dunal belt continues southward paralleling the shoreline.

Stop 6. Hellcat Swamp Nature Trail - This field stop coincides with another self-guiding nature trail and was selected because it exhibits relationships among a stabilized dunal system, a fresh water swamp and a salt marsh. A view of this area from the observation tower provides an opportunity to see these three systems (see road log directions). This stop shows a subclimax community. A man-made dike parallels the marsh shoreline which is artificially maintained to provide a breeding pond for waterfowl. The adjacent salt marsh is also a breeding area for waterfowl.

A consensus regarding the formation of the marsh is that the present marsh area was a fresh water swamp some 7,000 years ago. About 6,000 years ago sea level rose to encroach upon the fresh water swamp. The mixing of the two water masses created an estuarine environment. Evidence for these events is well recorded in the stratigraphic sequence of the marsh (McIntire and Morgan, 1963; Sammel, 1963; Hartwell, 1969; McCormick, 1969; Rhodes, 1973).

The substrate of the Hellcat Swamp varies from fine sand to clay. Much of the marsh is mixed clay-sand sediments while the swamp is composed of organic debris, sand and silt (Jerome and others, 1968). The sediment in the adjacent dunes is fine-grained quartz sand (Anan, 1969).

There appears to be evidence of dunal encroachment into the salt marsh area. Unvegetated lobes of sand can be observed from recent (1973) aerial photographs and from the observation tower. Thses features provide an opportunity to study vegetative succession through time.

Stop 7. Bar Head Drumlin and Beach - This area is the southern end of the longshore-transported sediments of an earlier geomorphic history (McIntire and Morgan, 1963). The large hill to which the barrier island is attached, is mapped as a drumlin (Sammel, 1963). This drumlin is partially eroded and provides an opportunity to study the cross-section of a glacially deposited feature. A drumlin boulder pavement is exposed on this beach at low tide one-half mile to the north. An excellent example of wave refraction can frequently be seen around this boulder pavement which forms a natural "groin." The rock types and mineral composition of the till clasts in both drumlins correlate with the bedrock of northern and western regions (Hartshorn, 1969).

The beach sediment is composed of very fine-grained quartz sand (McIntire and Morgan, 1963; Coastal Research Group, 1969). The cross-stratified dune sand is the finest sediment within the entire dunal system (Anan, 1969; Jones 1974). Frequently, there are thick layers of purple, garnet-rich, heavy minerals present at the swash zone. Hayes and others (1969) have observed heavy mineral layers throughout the Plum Island beach face. The commonly observed heavy minerals are biotite, garnet and hornblende.

Wind generated linear ripples appear to be the most common type of primary sedimentary structures found in this area. The Coastal Research Group (1969) observed an abundance of rill marks in the intertidal zone at this beach in addition to the ripples.

Stop 8. The Recurved Spit - This spit area is the most evident example of beach accretion at Plum Island. According to Farrell (1969) the spit has progressively grown since 1965. This growth is seen by comparing the 1966 Ipswich, Massachusetts, quadrangle to recent aerial photographs.

Hayes and others (1969) concluded that this spit receives the sediment supply from longshore drift and that the recurving results from wave refraction and tidal currents at the Parker River estuary. Farrell (1969) also observed a neep ridge and runnel system in the intertidal zone of this area.

Sediment in this system is very fine and lenses of organic debris are present a few feet down from the surface of the spit (Farrell, 1969). High energy conditions, however, introduce a coarse sand onto the spit face and Farrell (1969) observed that samples from these coarser beach faces were bimodal, indicating the possibility of a dual sediment source.

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DIRECTIONS AND MILEAGE LOG

The computed log starts at Stop 1 of this field guide and continues through Stops 7 and 8. The field stops included in this guide are found on Figure 6. Individulas using this field guide can choose the route most convenient for them to reach Plum Island, however, the best route from Newbury Center is Route 113 East, which coincides with Route 1A South. Follow 113 East – 1A South until the Newbury Common is on the right. Turn left at the flashing light onto Rolfe Lane. Stop 1 is at the intersection of Rolfe Lane with Seawall Street.

Figure 6.   Location map of field trip stops at Plum Island.

Plum Island is included in the Newburyport East (1966), Massachusetts, and the Ipswich, Massachusetts (1966), Quadrangles published by the United States Geological Survey. In addition, the Surficial Geology of the Ipswich, Massachusetts, Quadrangle (GQ 189) has been mapped by E. A. Sammel (1963) of the U. S. G. S.

0.0*   0.0ˣ   After turning left at the intersection of Rolfe Lane and Seawall Street, park the cars on the left side of Seawall Street near the white cottage.

Stop 1. Merrimack River estuary – This area is Joppa Flats. Note the High Water cord grass above the marsh high tide line. The red-roofed building at the northern end of Plum Island is near the mouth of the Merrimack River. The North Jetty is seen to the left across from this point.

Return to the cars and continue straight ahead to Plum Island.

1.0   1.0   The cottages at the left are built on stilts because of flooding in the marsh. The vegetation is primarily High Water cord grass. Seawall Street now becomes Plum Island Turnpike.

1.5   0.5   Crossing over the Plum Island River.

2.0   0.5   This is Plum Island Center. The land use found in this area is primarily residential and small service stores.

2.2   0.2   Intersection of Plum Island Turnpike with Northern Boulevard. Turn left.

2.5   0.3   Northern Boulevard parallels the shoreline. There is a noticeable paucity of vegetation along the discontinuous dune on the right. The residential development appears to control the environment.

3.6   1.1   Bear right and turn into the parking area to the right, parking near the red-roofed Coast Guard building. Walk between this building and the fence on the right. Continue to the beach which is about 75 yards straight ahead.

Stop 2. South Jetty area – At the beach turn right and follow the shoreline toward the mouth of the river. About 150 yards along the shoreline there is a dune segment. Walk up to the dune segment and continue along its base. The dune terminates at the beginning of the abandoned Coast Guard Station. You may wish to walk to the South Jetty; if so, the jetty is in sight 500 yards to the left. If you wish to return to the cars, turn right at the end of the dune and walk between this dune and the fence on the left. The parking area is about 150 yards straight ahead.

* Cumulative mileage
x Incremental mileage

Return to the cars and leave the parking area, turning left back onto Northern Boulevard. Proceed toward Plum Island Center.

4.5	0.9	The Basin is to the right. This feature was formed when the Merrimack River changed its course after 1827.
5.1	0.6	Turn left into the parking lot at the intersection of Northern Boulevard and Plum Island Turnpike. Park cars and walk 30 yards to the beach.

Stop 3. Plum Island Center Beach - See stop description no. 3 above.

Return to the cars and proceed west on Plum Island Turnpike.

5.3	0.2	Intersection of Plum Island Turnpike with Sunset Drive. Turn left and proceed south on Sunset Drive.
5.5	0.2	Note the development of the dunes and the amount of vegetation in this area. This area exhibits the relationship between the dune and vegetative stabilization and is contrasted with the northern end.
6.1	0.6	Proceed through the gatehouse into the Parker River National Wildlife Refuge. (OBEY ALL RULES AND REGULATIONS.)
6.2	0.1	Turn left into the first parking lot. Park cars as close to the beach as possible, but still within the parking lot.

Stop 4. Low Energy beach - Walk to the beach. Note the dunes and the slope of the beach. These dunes continue southward along the beach.

Return to the cars and turn left out of the parking lot back onto Island Road.

6.7	0.5	Far to the right is a bedrock outcrop (Pine Island).
7.1	0.4	Note the continuously stabilized dune on the left and the expanse of marsh on the right.
7.3	0.2	The pool at the right provides a feeding area for many species of birds.
7.7	0.4	Turn left into parking lot #6. This is Kettle Hole Nature Trail. Park the cars and walk to the beginning of the nature trail.

Stop 5. Kettle Hole Nature Trail - Follow the self-guiding nature trail to the left (DO NOT FOLLOW THE SIGN: "TO THE BEACH"). This trail slopes upward into the stabilized dunes. About half-way up this dune, note the garnet sands off to the left under a cover of Jack Pines (Pinus banksiana). Continue along the trail into the depression. An example of

a blow-out is seen from the summit of the rear dune, forming the back of the "kettle." Follow the trail around the depression.

Return to the cars. Turn back onto Island Road so that you are proceeding in the same direction as before (south).

8.4   0.7   Vegetative succession is seen in this area (Figure 5).

8.8   0.4   Bear left at this fork in the road. The Refuge sub-head-quarters is at the right.

9.0   0.2   The end of North Pool Dike is on the right.

9.3   0.3   This area on the right is a meadow used by migrating birds as a feeding ground.

9.4   0.1   On the left is a pine forest.

10.0   0.6   Note the height of the dunes to the left.

10.1   0.1   Turn right into parking lot #9. This is Hellcat Swamp Nature Trail. Park cars and proceed 100 yards to the observation tower.

Stop 6. Hellcat Swamp Nature Trail - From the observation tower look northward (Merrimack River estuary). The water below is the North Pool Dike. The area to the right of the dike is Hellcat Swamp. Turn around 180°; the water just below is the South Pool Dike and in the distance is the well-forested area of the "Pines."

Return to the parking lot. Follow the self-guiding nature trail from the parking lot into the Hellcat Swamp. Bear to the right 30 yards after the trail starts. Stay on this pear-shaped trail.

Note the vegetation along the trail. Continue on the trail until a circular clearing. Stay on the trail; there is another circular clearing within 50 yards. Follow the nature trail to the parking lot.

Return to the cars and proceed back to Island Road and turn right.

10.4   0.3   To the left is Camp Sea Haven (A summer camp for children with polio).

10.6   0.2   The "Pines" is on the right.

10.8   0.2   Note the expanse of salt marsh on the right.

11.2   0.4   The dunes to the left are well stabilized.

11.8   0.6   The dunes to the left are well stabilized by American beach grass.

12.0   0.2   Cross Farm Hill - This feature is mapped as a drumlin (Sammel, 1963). These fields are planted with grain for migrating bird

species. The beach dunes exhibit an expanse of American beach grass. This is another example of pioneer plants stabilizing the Plum Island dune fields. The upland area to the southwest is also a glacial feature; it was mapped as ground moraine and estuarine deposits (Sammel, 1963).

12.3   0.3   The Stage Island Pool complex is at the right. This area was mapped as ground moraine by Sammel (1963) (Fig. 2).

12.9   0.6   Turn right into parking lot #15. Park cars and follow trail from parking lot to the observation tower.

Stop 7a. From the tower, the Atlantic Ocean is to the East (the larger water mass). Bar Head drumlin is to the south, and Crane's Beach is directly across from this point. Plum Island Sound is to the west.

Return to parking lot #15. Directly across from this parking lot is a wooden walkway; proceed along this wooden walkway for 100 yards to the beach. Turn left (north) at the junction with the beach and walk toward the exposed rocks.

Stop 7b. Bar Head Drumlin Area - These exposed rocks are the boulder pavement described in stop description 7. Proceed southward toward the large hill. Examine the ripples found along this beach area and look for cross-stratification in some breeched dunes. The large hill is the Bar Head drumlin. Continue around the drumlin so that Crane's Beach is visible to the left across Plum Island Sound.

Stop 8. Recurved Spit - The recurved spit begins at the left just beyond the western end of the Bar Head drumlin. See stop description 8.

Return to the cars by following the western side (base) of the drumlin in a clockwise direction around (northwestward) until the intersection of the dirt road and the drumlin occurs. Turn right onto this road so that the drumlin is on the immediate right. Stay on this road for about 250 yards until the sign, "Entering Parker River National Wildlife Refuge." Turn left onto Island Road. Continue along Island Road for about 100 yards until you reach parking lot #15. Drive northward along Island Road, which becomes Sunset Drive, to Plum Island Turnpike. Turn left and return to Boston.

* END OF THE FIELD TRIP *

Trips A-9 & B-9

DYNAMICS OF SEDIMENTATION

AND

COASTAL GEOLOGY FROM BOSTON TO PLYMOUTH

by

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The coastal area south of Boston consists of glacial deposits, bedrock and recent marsh, dune and beach accumulations. In Nantasket Beach and Hull, no bedrock is exposed - only drumlins and prograding beach deposits. Outcrops of Mississippian (?) Mattapan Volcanics and Pennsylvanian or Permian Boston Bay Group are exposed at the south end of Nantasket Beach to the Ponkapoag fault (see Billings, this volume). South of Hingham to North Scituate Beach, Precambrian Dedham Granodiorite and the comagmatic Westwood Granite form many cliffed, irregular headlands. Southeast from North Scituate the coastline is more regular for the ground moraine and drumlins (First through Fourth Cliffs) present there are more easily eroded.

Glacial deposts constitute the principal source of beach material. Rivers contribute only a very minor fraction, except at Fourth Cliff. The exposures of bedrock show only slight erosion, so little material could have been derived from them. The beach sediment is composed of the same type of rock found in the till and gravel exposed in the drumlins such as Allerton and the numbered cliffs. The importance of the drumlins is shown by the presence of shingle near them. This shingle is progressively finer and less angular and smaller in quantity southward from the drumlins. On Nantasket beach shingle extends a little more than 2 km south of Allerton Hill. South of Fourth Cliff shingle is present for more than 3 km. The offshore,eroded drumlins and ground moraine also supply both sand and shingle to the beaches. This is especially noticeable at Nantasket Beach where the sediment becomes progressively finer south of the drumlin and then becomes coarser again.

That boulders can be moved by waves is best seen at the mouth of the North River inside the drumlin at Fourth Cliff. There, boulders 10-30 cm in diameter are spread out in almost a single layer 100-200 m wide on top of the flat surface of a peat bed.

Since the storms of greatest intensity on this coast are North East storms, the prevailing shore drift should be southward on sections of coast trending north south (ie Nantasket and

Scituate) and westward on sections of coasts trending east-west
(ie. between Nantasket and Cohasset Harbor) with local reversals
around headlands. Available evidence (Chute, 1949) shows that
beach material does not migrate to any appreciable amount around
promontories. Therefore each beach can be considered as a
separate unit when considering supply, movement and disposal
of beach sands and shingle.

ROAD LOG

Trip will assemble in the parking lot of Boston University
off Bay Street Road and Granby Street. Trip leaves at 8:30 A.M.
SHARP!

The bus will take city streets through Boston and Quincy.
To the uninitiated, a more relaxing route would be to take Route
128.

Cumulative Milage	Interval Milage	Start at the intersection of the Massachusetts Turnpike and Route 128
19.9	19.9	Route 3 South, bear right.
28.2	8.3	Exit at Route 228, towards Rockland and Nantasket. At end of intersection head towards Nantasket (left). Stay on Route 228 through South Hingham and Hingham.
31.5	3.3	Outcrops of Dedham Granodiorite on left.
37.4	5.9	Nantasket Beach. Follow the boulevard closest to the beach towards Allerton Hill.
38.7	1.3	Phipps Street, left.
39.7	1.0	Adams Street, left. Then right on Nantasket Ave. Straight ahead is Strawberry Hill, one of the six drumlins on Nantasket Beach. The steep bank on the east side of the hill is a wave cut cliff. Three hundred and fifty meters away is the present shoreline.
41.9	2.2	Sharp left, following the bay.
42.7	.6	Nantasket Ave, bear right.
43.0	.3	Harbor View Road, bear right.
43.3	.3	Lillian Jacobs School. Park in parking lot.

STOP ONE - View of Boston Harbor

About 180 drumlins have been recognized in the Boston Area
(LaForge, 1932) about 16 of them can be seen from this vantage
point. Your are standing on two coalescing drumlins which make up
the greater part of Hull. Behind you is Telegraph Hill (with the
tower) and Thornbush Hill. In front of you, a fine view of the
drumlins of Boston Harbor; from left to right, the three Brewster
Islands, Lovell Island, Georges Island (with Fort Warren), Gallops
Island (with the docks), Deer Island and Long Island. The long
axis of Gallops Island and the drumlin on Deer Island trends
S 75° E indicating the approximate direction of movement of the
continental glaciation in this locale. The average of all the
drumlins in the Boston Area is S 55° E. Some of the drumlins
in the harbor contain fragments of marine fossils gouged out
from the older marine clay and redeposited in the till of the
drumlins.

On Shag Rocks - just to the right of the Boston Lighthouse -
Cambridge Argillite is exposed. This uppermost member of the
Boston Bay Group (Pennsylvanian or Permian) is composed almost
totally of gray argillite with beds ranging in thickness between
0.13 - 7.6 cm, rhythmically alternating between lighter and
darker gray. The lighter grays are silty sands and sandy silts,
whereas the darker grays are clay and fine silts (Billings, this
volume).

Cumulative Milage	Interval Milage	Turn around and retrace the route to Allerton Hill.
43.6	.3	Bear left on Harbor View Road
43.9	.3	Nantasket Ave, bear left.
44.5	.6	Bear right, following the bay.
44.7	.2	Bear left and turn into parking lot. Park here and walk to the beach 200 meters to the east. On the beach turn left and walk to Allerton Hill and Point Allerton.

STOP TWO: Allerton Hill and Point Allerton

Allerton Hill, has been eroding on the average 60 cm per
year (Johnson, 1910). The eroded east side has exposed a good cross
section of a drumlin. The drumlin is composed of two recognizable
units: a upper unit of oxidized yellowish till and a lower unit
of unoxidized gray till. The gravels in both of the units are
primarily composed of discs and rods of Cambridge Argillite with
some Dedham Granodiorite, white quartzite ("Milton" ?) and a small
but noticeable fraction of red and purple rhyolites and andesites
of the Lynn Volcanics. These Mississippian (?) volcanics are
exposed in three areas north of Boston; from Winchester to Saugus,

West Medford to Lynn and at Marblehead.

In the sand and clay of the till, eleven species of mega-fossils have been found: (Source, Crosby, 1893)

	Telegraph Hill	Allerton Hill	Strawberry Hill
Balanus sp	X	X	
Tritia trivettata (Adams)		X	
Ilyanassa obselata (Stump)	X		
Crucibulum striatum (Say)	X		
Buccinum undatum (Linneus)		X	
Maya arenaria (Linneus)	X		
Venus mercenaria (Linneus)	X	X	X
Cyclocardia borealis (Conrad)	X	X	X
Astarte undata (Gould)	X	X	X
Scapharca transversa (Say)		X	X
Cliona sulphurea (Verrill)	X	X	X

At Point Allerton, a well developed cobble berm is present with an imbricated scarp. Wave refraction at the low tide plat-form refracts the waves such that two sets of waves approach the shore almost at right angles.

The diffraction and refraction of waves at the Point and their constructive and destructive interference with unaffected waves set up a series of cusps in the shingle south of the Point. These cusps are regularly spaced at about 4 m intervals. They gradually die out southwards. The spacing of the cusps will vary depending on the prevailing wave period.

Cumulative Milage	Interval Milage	From the parking lot turn left on Nantasket Ave.
44.9	.2	L Street, turn left. Then right on Beach Ave. Note the armored dunes on the right hand side. Some of the wind gaps have been filled in with shingle by the DPW.
45.5	.6	A Street, right. Then first left on Manumet Ave. At A Street the shingle on the beach is almost absent except at the berm line.
45.9	.4	Coburn Ave, left. First right, Beach Ave. Here the shingle on the beach is completely absent.
46.4	.5	Reverse Street, right. First left onto Manumet Ave.
50.0	.6	At the beginning of the sea wall at the Metropolitan District Commission Reservation, park.

STOP THREE: Nantasket Beach

The beach at Nantasket shows remarkable lack of change since the seventeen hundreds. Johnson (1910) remarks,
"A chart of Boston Harbor published in the fourth part of the English Pilot in 1709 while not accurate in detail seems to show that no pronounced changes in the shoreline of Nantasket Beach have occured in the last two hundred years."
It was not always that way. Nantasket at one time was a series of drumlins, which gradually, as sea level rose after the Pleistocene, were tied together by tombolos (Johnson, 1967; Figure 1).
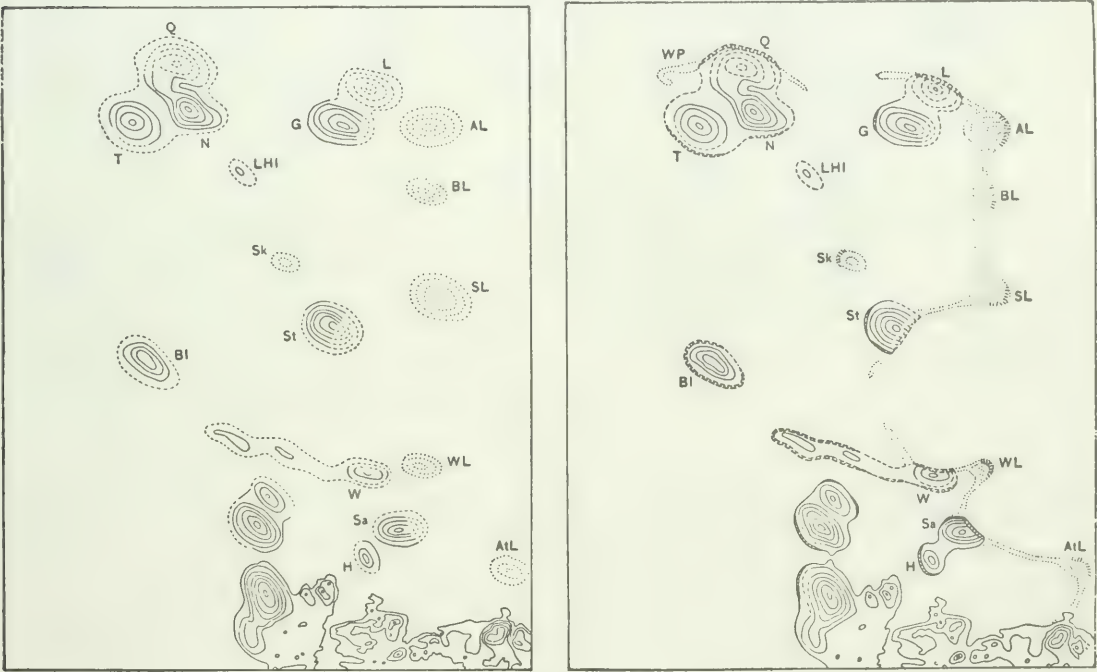
Figure 1 (from Johnson, 1967, p.467-469)

Initial stage of Nantasket
Beach complex tombolo.

Second stage in development
of Nantasket Beach tombolo.

AL	Allerton Lost Drumlin	Sa	Sagamore Hill
Atl	Atlantic Lost Drumlin	Sk	Skull Head Hill
BI	Bumkin Island	SL	Strawberry Lost Drumlin
BL	Bayside Lost Drumlin	St	Strawberry Hill
G	Great Hill	T	Thornbush Hill
H	Hamption Hill	W	White Head Hill
L	Little Hill	WL	White Head Lost Drumlin
LHI	Little Hog Island (Hog Is)	WE	World's End
N	Nantasket Hill (Telegraph)	WP	Wind Mill Point
Q	Quarter Ledge		
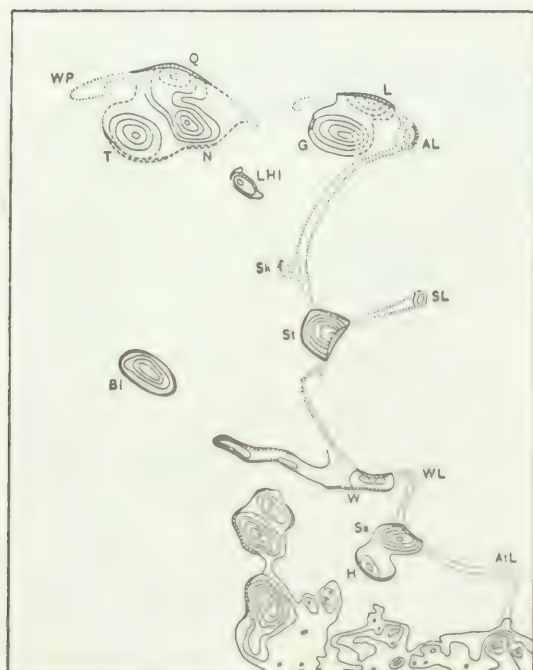
Third stage of development
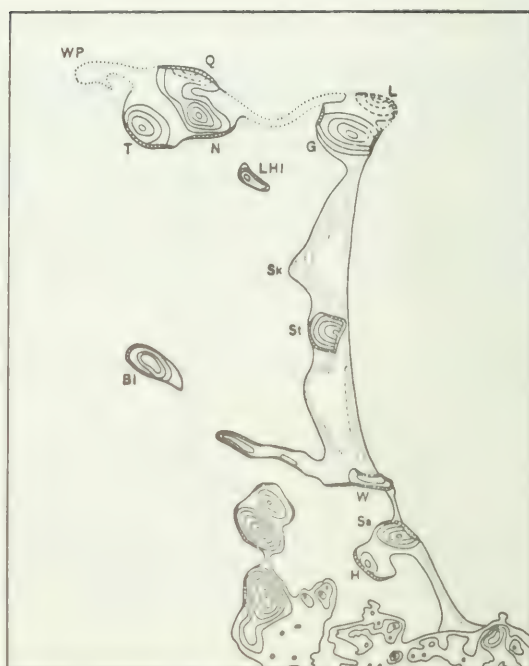
Fourth stage of development
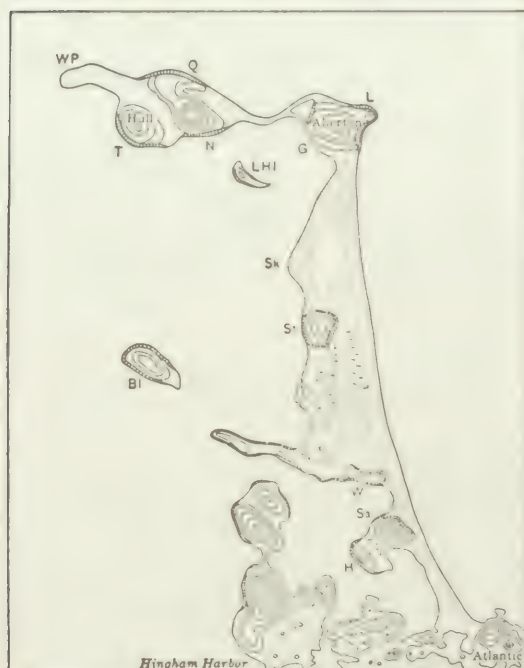
Present form of Nantasket Beach
complex tombolo

Theoretical future of Nantasket

Eventhough, the beach outline is now stable and therefore close to equilibrium, the wave energy is not evenly dispersed across the length of the beach. During periods of high waves, wave energy is focused at two localities, one near the north end of the beach and one south of the center of the beach, in between the eroding drumlins offshore (see figure 2).

The large scale refraction of waves over these obstacles causes a concentration of wave energy at these locations. The southern point shows consistent concentrations of energy for all directions of wave approach and in all tidal stages. The focal point does shift however, between 2.8 and 4.6 km south of Allerton Point. At high tide,the wave energy is more spread out along the beach and is not as focused. In figure two, only the shorter wave periods are shown. For longer periods, the wave focusing is not as intense due to extreme refraction where the wave orthogonals cross each other and therefore dissipate the total energy (Goldsmith, 1973).

In as much as Nantasket Beach faces at an angle to the dominant north east waves, there is a directional component of long shore drift. The southward diminishing sediment size from Point Allerton (Figure 2) indicates that at times there must be transport in that direction. Most of the sand on the beach ranges in size between 2 and 2.5 ϕ (.25-.177 mm) or fine sand. Two areas of coarser sand and gravel occur. These are shown by the sorting values on Figure 2. These coarse sediments are derived from the eroding drumlins offshore. Only near Point Allerton and opposite the coarse sediment offshore is the sediment on the beach very poorly sorted ($\sigma_I > 2.0\phi$). As can be seen from Figure 2, these areas of coarse sediment are slightly offset to the south from the main short period wave energy foci. The precise location of the increase in grain size or the presence of the gravel berm will depend on the prevailing wave period and direction and also the wave steepness. If a long period swell prevails the gravel may be buried under a layer of sand of varying thickness. Figure three shows the presence of the gravel near the high tide line at the MDC Reservation in November 1975.

Cumulative Interval   Turn left on Manumet Avenue.
Milage   Milage

  51.1   1.1   At the Atlantic Aquarium turn left and park.

STOP FOUR: ATLANTIC HILL AND LONG BEACH ROCK

At the south end of Nantasket Beach is Atlantic Hill. Here a good cross section of the basal volcanic units of the Mattapan Volcanics (Mississippian?) and the Pennsylvanian or Permian Boston Bay Group Sediments are exposed. This area is located on the south east margin of the Boston Basin within a north east plunging anticline. These units have been brought to the surface by the Blue Hill Thrust Fault.

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figure 2 Nantasket Beach sediment and
wave characteristics
(after Hayes, 1973)

deep water
ht(m) az
← 2   45°
  1   45°

0   1   2   3   ø   mean grain size   ----
                                    δ   standard deviation ——

                                    m   projected wave ht. ------
                                         at lowtide
1.5   3.0

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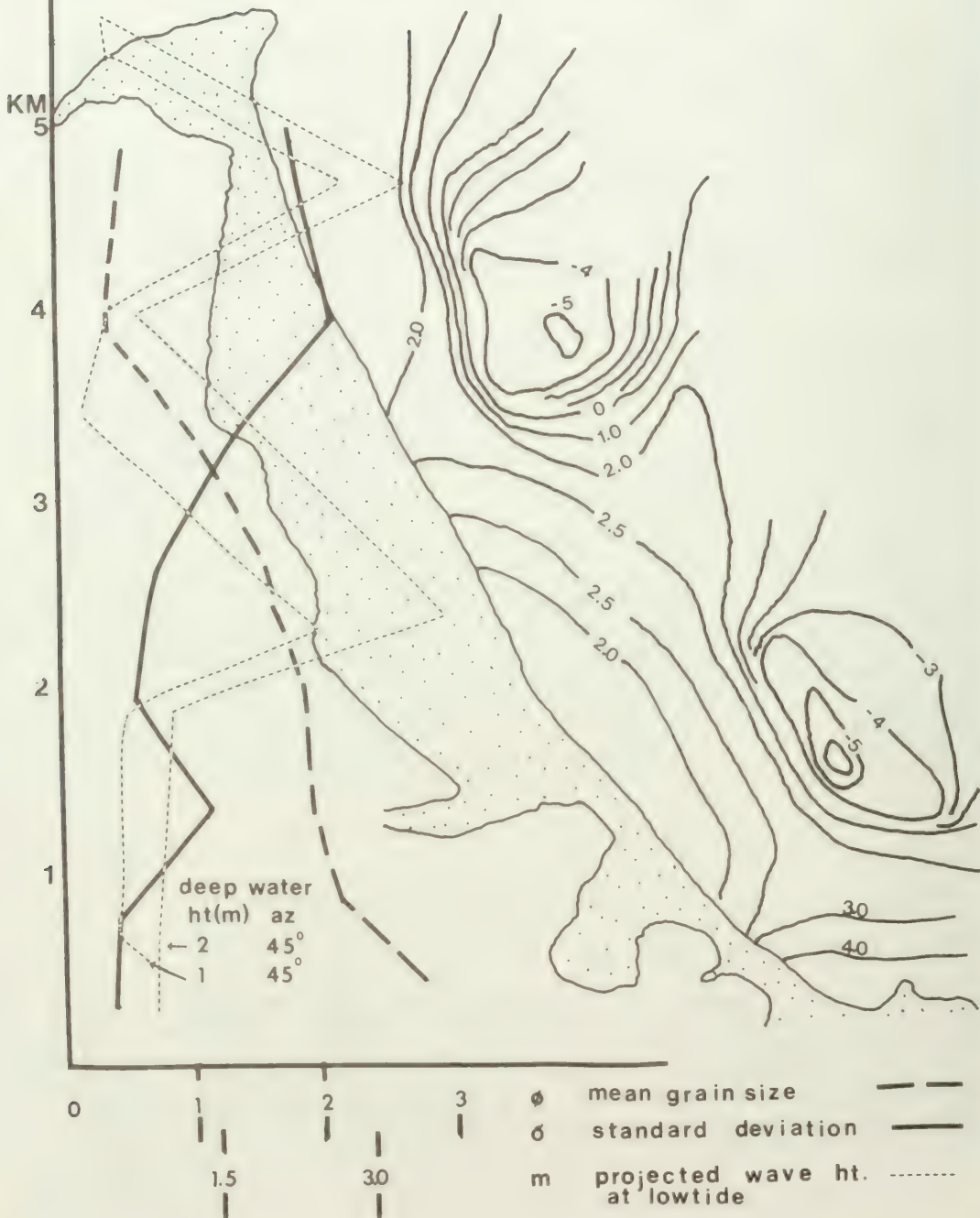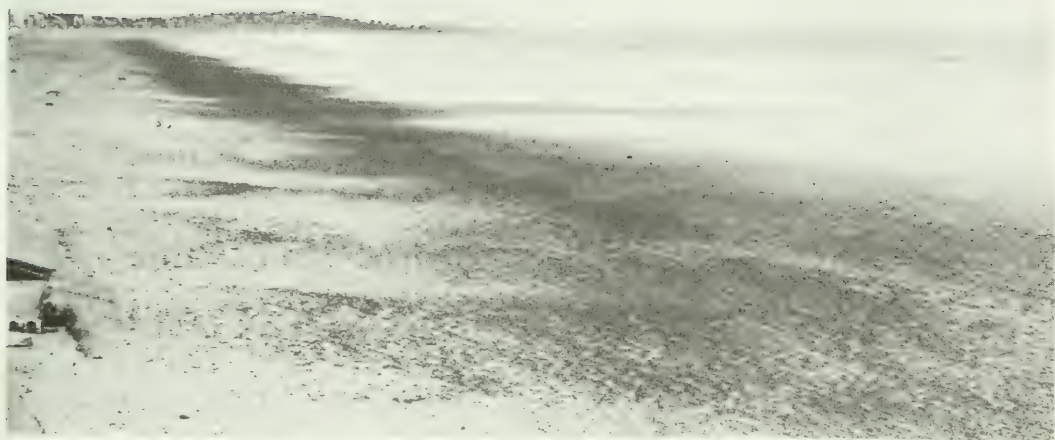
Figure 3. Cuspate gravel deposit near the middle of Nantasket
Beach, November 1975.

Figure 4. Water lain ash unit and coarser volcanic fragments
of the Mattapan Volcanic Complex at Atlantic Hill.

Just left of the restaurant "The Ledges" is a hard, dense greenish gray andesite lava about 18 m thick. These andesites are pillowed, as outlined by the lighter green epidote veins. They also contain bombs. Above the andesite is a 9 m bedded tuff (strike N65°E, dip 25°SE). This layer is a water lain ash deposit (see figure 4). Parts of this layer may be lahars. In the upper part of this unit there are many coarse volcanic fragments. Above this are thin lenticular beds of andesite and tuff. The hill is capped by another greenish gray andesite lava. These andesites are deuterically altered. Plagioclase, chlorite and epidote are the major constituents plus accessory magnetite. There is little primary quartz, but quartz and calcite may be abundant as secondary minerals (Bell, 1964, Skehan, 1975).

Below the andesites and best exposed at low tide on Long Beach Rock is the sedimentary sequence of the Boston Bay Group. The lowest units, to be seen only at low tide on the north side of Long Beach Rock, are tuffaceous conglomerates and agglomerates which include fragments of the underlying Dedham Granodiorite and Lynn Volcanics and also arkose boulders. Above this are 45 cm thick beds of intercalated red sandstone and 15-30 cm layers of banded green porcelaneous shale. These thin beds show brecciation and penecontemporaneous faulting and baking. The contact between the volcanics and the sediments can also be seen at the base of the cliff (around the corner from the restaurant).

The dikes, especially those on Long Beach Rock are parallel to the local faulting and seem to be related to the volcanic activity that produced the andesite flows. The dikes predate the faulting (Crosby, 1893).

Cumulative Milage	Interval Milage	From the parking lot turn left onto Nantasket Ave.
51.2	.1	Atlantic Ave, turn left.

Here is the approximate location of the southernmost of the Boston Basin Faults - Ponkapoag Fault. Although it now dips 80° NW with the Precambrian Dedham Granodiorite on the south and the Boston Bay Group on the north, it is presumed that the fault originally dipped south and was rotated to its present position. In Hingham, the stratigraphic throw is at least 400 meters (Billings and others, 1939).

| 52.7 | 1.5 | Bear left, staying on Atlantic Avenue. |

From here to Cohasset, on both sides of the road three types of acidic intrusives crop out.
Unnamed medium gray, foliated, biotite granite composed of 30-60% plagioclase, much altered to sericite, epidote and albite; 10-35% K spar as orthoclase, microperthite and microcline; 5%

secondary olivine green biotite and accessory magnetite. This granite commonly has sodic plagioclase phenocrysts. It intrudes the Westwood Granite (Chute, 1965).

Westwood Granite is a pinkish gray, fine to medium grained granite with 25-35% quartz, 15-30% albite, 35-50% microperthite, with accessory apatite, sphene and magnetite. It is similar to the Dedham but finer grained. In the Blue Hill, 40 km to the north, the Westwood intrudes the Dedham, but it probably belongs to the same magma series (Chute, 1965).

Dedham Granodiorite isa foliated light pinkish gray, medium grained granodiorite with 25% quartz, 10% altered biotite and the remainder saussuritized plagioclase and orthoclase. It contains many xenoliths which are of two types, a diorite or a fine grained amphibolite. The amphibolites are orientated and give the grano-diorite a conspicuously green color owing to the abundance of chlorite. The amphibolite is grayish green, thin to thickly layered in which the layers have fine alterations of felsic and mafic minerals producing a striped appearance. Hornblende and plagioclase are the principal component minerals with chlorite, quartz, epidote, sphene and calcite also present. The granite has a foliated texture that parallels that of the xenoliths (Nelson, 1975).

Cumulative Milage	Interval Milage	
54.8	2.1	Bear left at intersection.
55.4	.6	View of Cohasset Harbor
55.7	.3	Cove Road, left and immediately left on Border Street Road.
56.1	.4	Reversing falls of "The Gulf"
57.5	1.4	Garnet Road, left.
58.1	.6	Hatherly Road, right (at light).
59.1	1.0	Mann Hill Road, left. Park at the bottom of the hill.

STOP FIVE: Mann Hill Beach

Mann Hill Beach is a shingle bay mouth bar.At low tide a sand bar can be seen. This sand bar stretches across the entire length of the gravel bar. The shingle reaches 10 m above low water and shows well developed imbrication, several berm lines and cusps. The pebbles and cobbles are shape sorted (figure 5), disc shaped at the berm and in the imbricated zone and spherical and rod shaped seawards of that zone.(Zingg, 1935).
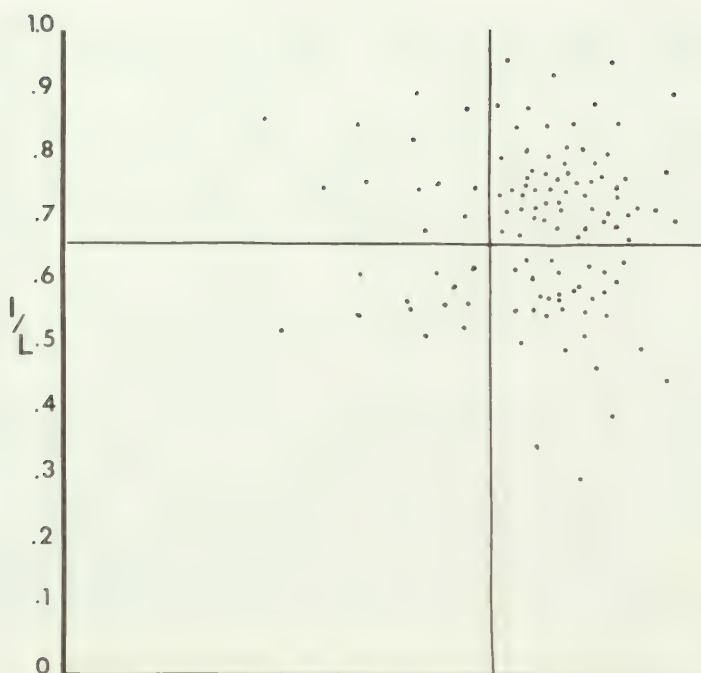
figure 5

4th cliff
front edge
of shingle
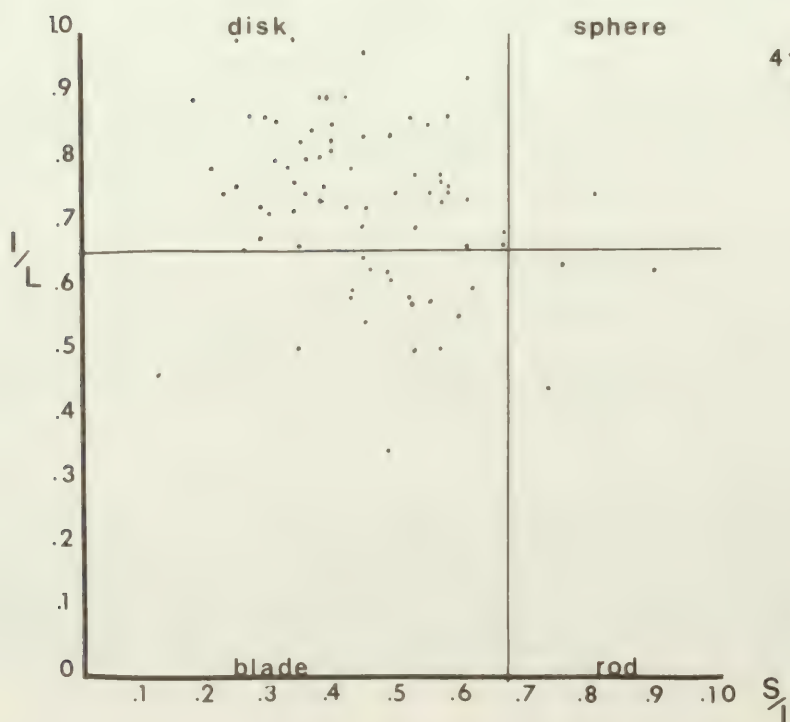
4th cliff
overwash

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Net landward movement of the pebbles during normal sea
conditions is small. During storms, pebbles of all shapes are
brought in by waves from the offshore tills and ground moraine.
Discs, being lighter than a sphere of the same mean diameter and
having a lower settling velocity than any other shaped pebble are
thrown up higher on the beach (Krumbein, 1939, McNown and Malaika,
1950). Once gravel is high up on the berm, a sorting mechanism
takes place. Backwash moving through the gravel, moves the finer
sizes seawards (Bluck, 1967). The size and shape of this seaward
moving gravel is dependent on the size and geometry of the pore
space. Usually a fringe of spherical pebbles is found at the
high tide water line. These probably have been moved through the
pore spaces. Rods, however, are caught in the intersticies, for
they orient themselves with the long axis parallel to the beach.

Seaward movement of the surface particles on the berm scarp
takes place under normal conditions. In a traction carpet, spheri-
cal and rod shaped particles move faster than discs, for discs
have a lower pivotability (Kuenen, 1964). Therefore spheres and
rods will be transported further seaward by the backwash. Almost
always, there is a fringe of spherical and rod shaped shingle
seaward of the gravel bar (see figure 5).

While the discs lag behing, they are not stationary. They
become imbricated. Perculation by the backwash produces an
imbrication of the pebbles, such that they dip seawards. By means
of a caterpillar type action these discs are slowly moved sea-
wards. This movement is irregular, resulting in a wide range of
dip values (0-85°).

Diffraction and refraction of waves around Cowen Rocks
0.7 km offshore (the only outcroping of Dedhan Granodiorite in the
Scituate Quadrangle) may set up an interference pattern between
these waves and unaffected incoming waves such that cusps are
usually well developed on Mann Hill Beach. Cusps may also be
due to the interaction of transversal waves (edge waves) which
are excited by incident waves and the incident waves themselves.
Edge waves are surface waves trapped by refraction to the shore
and have a maximum amplitude at the shore line. The interaction
between these edge waves and incident waves effects the breaker
height along the shore and may set up a circulation pattern in the
nearshore consisting of an onshore flow towards the breakers,a
longshore current and an offshore flow in a strong, narrow rip
current. These rip currents are located at the antinodes of the
edge waves (Bowen, 1969, 1973).

Once this circulation is set up cusps develop. Cusps on a
sandy beach are first noticeable as patches, a few centimeters
thick,of gravel, shells or other coarse material. The backwash,
instead of returning in dispersed flow, moves away from the patches
and returns in a channel. This process is repeated and intensi-
fied till the backwash flow attains such momentum that the next
swash cannot proceed against it and is projected onto the apices
of the developing cusp. There the coarsest particles are deposited

while the finer grains stay entrained as the water swings into the adjacent bays without stopping (Bagnold, 1940). These apices become more and more imbricated with each passing high tide. The cusps will be reoriented or eradicated by a change in the sea state.

Cumulative Milage	Interval Milage	Return to Mann Hill Road. Cross Hatherly Road.
59.6	.5	Bear left, staying on Mann Hill Road.
60.3	.7	Bear right, staying on Mann Hill Road.
60.5	.2	Curtis Road, left.
60.9	.4	Shallow left onto Country Way.
		You are now driving over ground moraine deposits, non sorted and unstratified drift with a mixture of sizes ranging from clay to boulders. From test borings, it appears that the moraine is from 30-600 cm thick (Chute, 1965).
63.5	2.6	Left, to join route 3A south towards Marshfield.
64.6	1.1	Cross the North River.

From 1646 to 1871 the North River was known as the cradle of New England Shipbuilding. More than 1,000 vessels were constructed in over 20 shipyards on this river. The most famous of these ships were the Beaver, one of the vessels raided by the Boston Tea Party and the Columbia, the first american ship to circumnavigate the world. There was a plentiful supply of timber, white oak, black walnut and white pine. Demands for larger ships led to two unsuccessful attempts to breach the barrier between Third and Fourth Cliffs, for in the nineteen hundreds the mouth of the North River was 4.8 km south of its present location, flowing for that distance behind a narrow barrier beach.(Spayne, 1975)

64.9	.3	Shore Road, left towards Seaview and Humarock.
65.7	.8	Humarock Street, left.
68.0	2.3	Sea Street, left.
68.4	.4	Cross South River
68.5	.1	Central Avenue, left.

69.9   1.4   Go to the Military Reservation and park.
                       Walk along the beach to the base of the
                       drumlin and then around the drumlin to the
                       spit and bar.

STOP SIX: Fourth Cliff and spit and sand bar in the South River

    Fourth Cliff is a 24 m high, 0.8 km long drumlin that consists
of 12-30 cm of soil and 9 m of brown oxidized till which grades
downwards into incompletely oxidized till. In this lower unit
there are remnants of unoxidized gray till that contain some reed
like plant remains. These have been dated at 35,000 B.P. (Chute,
1965). The typical amount of silt and clay in the till is 19%
with a maximum of 40%. This is an unusually low percentage for
eastern Massachusetts drumlins.

    On the east side of the drumlin two lenses of sand and
gravel 3-4.5 m thick separated by 3 m of till, crop out. These
lenses dip 10° to the south and appear to pinch out at the
bottom of the cliff (figure 6). The composition of the pebbles
and cobbles in the till is primarily Dedham Granodiorite and
Westwood Granite and biotite granite and Mattapan Volcanics.
The Cambridge Argillite is no longer present in large quantities.
The sand is 60% quartz, 20% feldspars and 20% heavy minerals
such as biotite, magnetite, garnet and hornblende.

Figure 6. East side of Fourth Cliff, Scituate Massachusetts and
          the shingle berm in front of the till. Note the
          layering of the sand and gravel in the drumlin.

On the beach are many boulders and cobbles some of which
are so large that even storm waves have difficulty in moving them.
As you walk along, make sure you see the large (1.2m) Dedham
Granodiorite boulder with the orientated xenoliths of amphibolite.
On the north east point there is a boulder pavement. It has an
exposed width of 60-100 m at low tide. Of interest is that there
seems to be little or no sand movement across this boulder
platform below mid-tide level. The boulders below this level show
little or no abrasion; instead they are covered with barnacles
and seaweed and many show weathered surfaces that would not
survive under abrasion. In contrast, the boulders on the upper
part of the beach between the base of the wave cut cliff and mid-
tide show evidence of abrasion. There are few weathered surfaces
or flora and fauna that could survive above the mid-tide level.
This scouring is caused by sand and shingle which is washed back
and forth at the still stand of the high tide. Above the mid-
tide level, the shingle extends about 4 km south of Fourth Cliff.
Beyond that, the beach is composed entirely of sand.

Before the nineteen hundreds there existed a barrier between
Third and Fourth Cliffs. The mouth of the North River was 4.8 km
south of its present location. Then on November 27th, 1898 with
a high tide of 4.5 m (1.3 m above normal) and a wind of 120-130
km/h piling up waves even higher, the ocean cut through the
beach ridge between the cliffs. In a few hours a channel 45 m
wide and 3 m deep had been excavated. Now the channel is 120 m
wide and 4.2-4.8 m deep. The average flood tidal velocity
through the gap is 24 cm/sec. The ebb tide velocity is 36 cm/sec.

It took three years of longshore drifting to fill the old
river entrance. The result is that the South River now flows
further north and has developed a sand bar which extends into
the North River which recurves it. The bar, now, is almost a
reverse mirror image of Cape Cod.

The spit behind Fourth Cliff can be divided into two distinct
parts. The first part is adjacent to the drumlin. It is fronted
by a low scarp 60 cm high and is composed almost entirely of
boulders and cobbles. These cannot have come from the drumlin
immediately behind the beach for the sizes there are much smaller.
Instead, they must have been carried by storm waves around the
north-east point.

About 200 m southwest of the point there is a sudden change
in the size of the shingle. The particles become much smaller
and sand becomes dominant (see table on the next page). This may
demark the boundary of the effect of storm waves. Also there is
a scarp of old marsh grass (Spartina patens) there and only the
largest storm waves can lift cobbles over this resistant scarp.

From there south westward, sand predominates. The development
of the spit has dammed up the sediment coming down the South River.
This is now deposted in a sand bar. This bar where it extends into

the North River, recurves back to Fourth Cliff. At the north-west corner, the bar has become anchored by extensive beds of mussels. The top of the bar is practically devoid of vegitation or animal life. But sand waves, current ripple marks and rhomboid ripples and rill marks are common.

Table 2. Size analysis of the spit and sand bar at Fourth Cliff (after Spayne, 1975)

φ	1	2	3	4	5	6	
> -1		42	96	37			1. dune line
-1-0	<1	<1	1	38			2. high water line
0-1	12	19	<1	19	28	12	3. top of bank at beach front
1-2	50	30	1	4	63	56	4. bank at beach front
2-3	38	9	2	2	7	31	5. mid bar
3-4	1	1	<1	<1	1	1	6. north-west edge of bar

Cumulative Milage	Interval Milage	Return along Central Ave.
71.3	1.4	Sea Street, right.
71.7	.4	After the bridge turn left on Berry Street.
73.0	1.3	Ferry Street, right.
73.6	.6	Bear left staying on Ferry Street.
74.5	.9	Furnace Street, right.
75.9	1.4	Bear right. Merge with Route 139.
76.2	.3	Entrance to Route 3 to Boston via the SouthEast Expressway or Route 128.

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COASTAL GEOLOGY AND GEOMORPHOLOGY OF CAPE COD -
AN AERIAL AND GROUND VIEW

by

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INTRODUCTION

Cape Cod is a showplace of the results of the actions of geologic agents both past and present. This trip will include three separate, but integrated sections concerning modern coastal processes and past-glacial history. By means of an aerial overflight, coupled with selected ground trips, participants may view the process-response interactions of this dynamic area in a macro, meso and microscale frame of reference.

Section A (Macroscale) is an aerial overflight of the entire Cape Cod region, including the islands of Nantucket and Martha's Vineyard. Dynamic process interactions and their resultant geomorphic features will be viewed from the air. A better understanding of the complex area can be achieved through this macroscale overview.

Section B (Mesoscale) is a look at coastal geology and glacial geomorphology of the Atlantic shore of Cape Cod, north of Coast Guard Beach (Section C). On this section, the regional coastal erosion and deposition related to shoreline fulcrum, nodal points, wave refraction, and wave dynamics will be examined.

Section C (Microscale) is a detailed look at the processes occurring on Nauset spit. Through a series of cores and trenches, participants will study the area's geologic history, inlets and overwash fans. The interaction of vegetation and geological processes will also be examined with a look at plants as geological agents responding to

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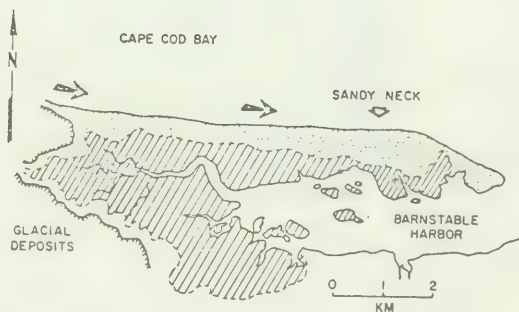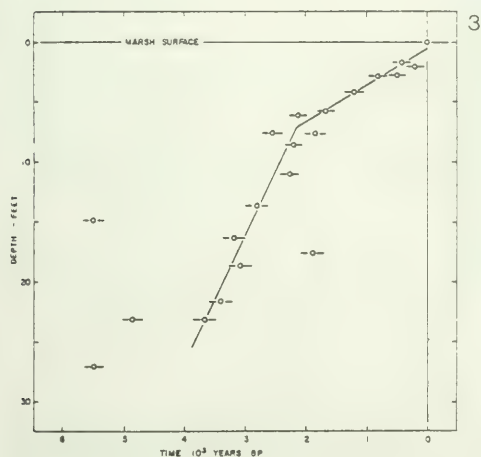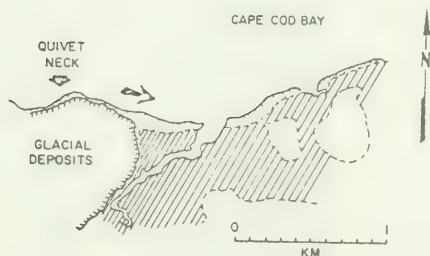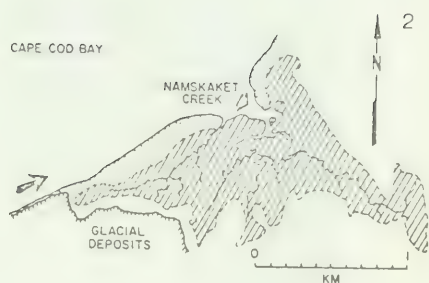
FIG. 1.   Index Map to Section A (Macroscale View).   Letters Indicate
Areas Covered in Field Guide.   Note that Areas in Between Letters
Will be Discussed on the Trip.

FIG. 2.   Examples of Eastward Spit Growth at Sandy Neck, Quivet
Neck and Namskaket Creek.   Stipled Areas are Sand Spits.   The
Cross-Hatched Areas are Salt Marsh Protected from Wave Action by
the Sand Spits.

FIG. 3.   Age and Depth Below Marsh Surface of Peat and Wood Samples
Collected in the Town of Barnstable, Massachusetts.   Circles with
Lines are Data Points.   (From Redfield and Rubin, 1962).

aeolian sand transport, overwash and inlet dynamics. The ecological zonation resulting from these geological processes and salt spray will be discussed.

Since space limitations in this field guide prohibit a detailed introduction to the general glacial history and origin of Cape Cod, participants are strongly urged to review Strahler (1966), Shepard and Wanless (1971) and Fisher (1972). Moreover, a revised surficial map and writeup of Cape Cod will be supplied to participants at trip time courtesy of the U.S.G.S. through Robert Oldale.

SECTION A
A MACROSCALE VIEW

Through the use of an aerial overflight, we will view the entire Cape Cod region. The flight will commence at Hyannis airport and should take about 1.5 hours. Prior to this trip participants are *strongly* encouraged to read Shepard and Wanless (1971) p. 29-32 and p. 41-57. If participants plan to take photographs, they are urged to read Kodak Technical publication M-5 entitled, "Photography from Light Planes and Helicopters."

Figure 1 shows the general areas that the flight will cover, and these letters are referred to in the overflight descriptions.

The leaders of this section are Jay E. Leonard and John J. Fisher. Contributions to this field guide section were made by Victor Gold-smith, Clifford A. Kaye, Harold P. Nilsson and Peter S. Rosen.

Area A and B - South and East Shore of Cape Cod Bay. One of the most prominent features along the southern shore of Cape Cod Bay is Barnstable Harbor and salt marsh, separated from the bay by Sandy Neck (Fig. 2). In their classical study of the Barnstable salt marsh, Redfield and Rubin (1962) found that high marsh peat (*S. Patens*) is naturally formed within a limited tidal range and provides a reliable indicator of the rate of rise in sea level. Radiocarbon dating of peat from the Barnstable marsh by Redfield and Rubin (1962) is shown in Fig. 3. The data show that in the Cape Cod area there has been a continuous rise in sea level for at least the last 3,700 years. The average rate slowed abruptly at about 2,100 B.P. Redfield and Rubin speculate that this change in the rate of sea level rise marks the termination of eustatic change and that subsequent rise was due principally to subsidence.

Eastward from Barnstable Harbor are two smaller marsh-sand-spit systems at Quivet Neck and Namskaket Creek. The origin of these systems is analogous to that of the Barnstable marsh. With rising sea level, salt marsh systems develop in topographic lows. Concurrently, sand spits accumulate between the marshes and the main water body and act as barriers to waves. The net west-to-east longshore drift along the south shore of Cape Cod Bay is responsible for the sand spit formation and generally forces tidal creek entrances to migrate eastward. Figure 2 displays maps of all three marsh-spit systems for comparison.

FIG. 4. Aerial Photo of the Brewster Tidal Flats Looking Westward. Visible Features Include Crescent-Shaped Swash Bars, Curved Tidal Drainage Channels, Eastward Longshore Drift Shown by Sand Trapped by Groins.

FIG. 5. Multiple Sand Bars Parallel to the Shoreline on the Eastham Tidal Flats. Approximately 30 Bars are Visible.

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FIG. 7. Jeremy Point and Billingsgate Island Looking Southward. Two Intersecting Multiple Bar Systems are Visible. One is Formed by Westerly Winter Winds and the Other by Southwesterly Summer Winds.

FIG. 6. Oblique or Transverse Bars on the Northern Eastham Tidal Flats. Multiple Sand Bars Intersect the Oblique Bars.

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Tidal Flats. Extensive tidal flats are developed in southeastern Cape Cod Bay. They begin just eastward of Sesuit Harbor and extend along the bight of the bay shoreline into Wellfleet Harbor. From Jeremy Point, the flats narrow northward toward Truro. The fundamental cause of the tidal flats is a combination of a large tidal range (approximately 3 m) and gradually sloping glacial outwash plains. Littoral processes, brought twice daily by the tides, have eroded the relatively flat outwash plains which slope gently toward the sea. The post-Pleistorene rise at sea level is also partially responsible for the lateral extent of the tidal flats.

The Brewster flats roughly begin just eastward of Sesuit Harbor and extend to Rock Harbor (Fig. 4). The Brewster tidal flats display a complex assemblage of spits, crescent-shaped sand bars and tidal channels. The complexity of the Brewster flats may be due to an originally irregular topography over which the sea has transgressed.

The Eastham tidal flats (Fig. 5) are roughly delimited by Rock Harbor to the south and Wellfleet Harbor to the north. The Eastham flats extend seaward about 2 km to mean low water. They are covered by a prominent system of multiple sand bars, parallel to the coastline. As many as thirty bars may exist which are very regular in appearance. Individual bars may be traced for over 1 km. Aiding the visual prominence of these sand bars from the air is the fact that bar troughs serve as environments for marine organisms -- especially algae. Bar crests are generally void of marine life since they are exposed to vigorous wave action.

At the northern end of the Eastham flats another type of sand bar, oblique or transverse to the shoreline, intersects the multiple sand bars (Fig. 6).

Directly westward, one may find Billingsgate Island and Jeremy Point. Billingsgate Island no longer deserves the name island, as it is now entirely submerged at high tides. In more fortunate times, Billingsgate was occupied by three lighthouses and a fishing village. The tidal flats from Jeremy Point northward exhibit systems of sand bars similar to the multiple bars of the Eastham flats (Fig. 7). One system is roughly parallel to the shoreline and the other is elongated northwest to southeast. These intersecting bar systems are developed on flats narrowing northward toward Truro.

Sand Bar Origins. Multiple sand bars, parallel to the shoreline, as displayed in Eastham, and less regularly developed on the Brewster flats have been reported from many locations. All occurrences have several features in common:

(1) Multiple sand bars are developed in relatively low energy environments (sounds, bays, lagoons, etc.).
(2) The bars exist only where there is an abundant supply of sand-sized sediment.
(3) Bars are developed on low bottom slope gradients; the less the slope, the greater the number of bars.
(4) The sand bars are developed to a depth which is approximately equal to the first break point of incident waves at mean low water.

Multiple sand bars appear to be formed by waves produced by
the direction of dominant wind. In the case of southeastern Cape
od, the dominant winter winds are from the west and northwest.
outhwest winds are dominant in summertime.

The very regular bars on the Eastham flats are developed by
inter waves, since the area is relatively sheltered from summer waves.
orthward, the shoreline is exposed to both winter and summer waves.
he bars parallel to the shore are due to winter waves. The oblique
ars are oriented roughly normal to southwest (summer) waves. The
ars on the Brewster flats originate basically the same way as in the
ther areas, but are complicated by an irregular inherited topography.

The oblique bars on the northern Eastham tidal flats are enigmatic.
t appears that they are formed by tidal currents entering and leaving
ellfleet Harbor (Nilsson, 1973).

The specific mechanism(s) by which the multiple sand bars are
ormed are poorly understood. Carter, and others (1973) and Lau and
ravis (1973) believe that the bars are formed by current cells di-
ected from the troughs toward the crests. The current cells are
ormed by the interference of the incident waves and a partically re-
lected component of them.

rea C and D - The Provincelands and the Outershore. Participants are
rged to refer to Shepard and Wanless (1971) and Section B of this
ield guide for descriptions.

rea E and F - Nauset-Monomoy Island Barrier-Spit Complex. Monomoy
sland and Nauset Spit are located on the "elbow" of Cape Cod,
assachusetts (Fig. 1). They were formed in Holocene time as a
ingle sand spit in response to the longshore currents resulting from
he dominant northeast waves impinging upon the outer beach of Cape
od. Since 1620, Monomoy and Nauset spits have undergone at least two,
nd probably three, cycles of large-scale inlet migration (Goldsmith,
969). The latest cycle began in 1846 with a natural breach across
auset Spit caused by the shoaling up of the former inlet, which in
844 was about 2 miles south of where it was in 1971. The shifting
f the inlet is due to the growth of Nauset Spit approximately six
iles to the south since 1846.

"Scars" remaining from this last cycle of inlet migration, and of
he former inlet location, are quite apparent from the air (1, 2, 6
nd 7 below):

(1) Erosion on the west side of Chatham Harbor in the Chatham
Light vicinity, in the late 1800's when the inlet was opposite
this location, forced the relocation of the light house.
(2) The severe offset to the west of Monomoy Island, relative to
the new Nauset Spit growth.
(3) Previous to the late 1950's, Monomoy was connected to Morris
Island, a glacial outwash feature. Morris Island was not
connected to Chatham. The natural response to the construc-
tion of the artificial causeway between Morris Island and
Chatham was a breakthrough in the Morris-Monomoy connection.
An extensive flood tidal delta has formed between Morris
Island and Monomoy Island since about 1960, when the break-
through occurred. The rather extensive nature of the

deposition (and perhaps even the breakthrough) could have been predicted by consulting the tide tables which show a marked difference in times and heights of tides between the ocean and bay sides of Monomoy.

(4) The relatively small ebb tidal delta is in marked contrast to this flood delta and reflects scale in processes. Bed-forms have been studied by Hine (1975).

(5) Extensive wave refraction around the ebb delta results in wave energy concentration slightly south of the landward end of the southwest part of the tidal delta, resulting in greatly increased erosion. However, because of refraction, all waves tend to approach this spot from the southeast. As a result, the end of the tidal delta is migrating north-west, and therefore, so is the zone of severe erosion. The wave refraction pattern should be visible from the air.

(6) The site of the old inlet, about 1/3 of the way down Monomoy at the narrowest portion of the island, is quite apparent. Prior to 1846, this inlet marked both the north end of Monomoy and the south end of a continuous Nauset Spit. Fur-ther evidence of the cyclic nature of this inlet cycle was apparent in December, 1974, when the ocean once again broke through in this same spot, though the new opening "healed" within 10 days. The flood delta created during this short period of opening should be apparent.

(7) Further to the west, the very extensive delta formed about 150 years ago, is quite apparent, and is now called the "com-mons", a site of abundant shellfish. Changes observed on Monomoy since June 1968 have been equally dynamic (Goldsmith, 1972). Large-scale accretion occurs on the southwest and southeast portions of the island. Three years of biweekly observations of twelve permanent beach profile stations on Monomoy and four on Nauset Spit has revealed major variations in the amount of erosion and deposition taking place along the shoreline (Goldsmith and Colonell, 1972). The maximum erosion observed was 151 feet of beach retreat (amounting to 2300 cubic feet of sand per linear foot of beach) between June 1968 and March 1970, which occurred at the M-6 profile location approxi-mately 0.25 km south of this recent breakthrough. The large variations in the amount of erosion measured along these pro-files are related to an unequal wave-energy distribution within wave fronts impinging on the shore.

(8) This unequal wave-energy distribution is attributed to wave refraction around the irregular bathymetry offshore from Monomoy-Nauset, resulting in five shoreline protuberances of sand in six miles of Monomoy shoreline. These protuberances are flanked updrift by erosional zones and downdrift by ac-cretional zones. Moreover, annual changes in rates of erosion along any one profile indicate that these zones of erosion and deposition migrate along the beach. These protuberances, which are quite apparent in the air, are formed on nearly all coastlines, though the spacing varies considerably and is a function of incoming wave energy.

Wave behavior near Monomoy was analyzed with the aid of over 200 wave refraction diagrams. The results indicate that the nonuniform distribution on wave energy along the Monomoy shoreline is due primarily to refraction of long (8-12 sec) waves of low amplitude. The larger amplitude, long-period

waves (height >5 ft) tend to break too far from the beach
to produce zones of wave-energy concentration, and the
shorter waves (<7 sec) do not refract sufficiently to
produce the zones of wave-energy concentration observed
on Monomoy. Furthermore, the wave refraction may have
been instrumental in forming and maintaining the shape and
orientation of the northeast-oriented linear depositional
sand bodies which make up a large portion of the irregular
offshore bathymetry.

(9) Nearshore processes have produced three distinct types of
offshore bars: (a) subtidal bars oriented oblique or
perpendicular to the shoreline and attached to areas of
the shore undergoing large amounts of erosion; (b) subtidal
bars parallel with the shoreline and located >2000 ft off
portions of the shoreline undergoing relatively small amounts
of beach erosion or accretion; (c) large intertidal bars
oriented obliquely to the shoreline and associated with the
formation of the ebb-tidal delta and the resulting wave-
refraction patterns. Types (a) and (c) should be easily
apparent from the air, (b) will be indicated only if there
are long-period swells present.

(10) The southern 2/3 of Monomoy, marked by high vegetated dunes
(about 10 m.), is much more stable, though data of unknown
accuracy suggests that this portion has retreated westward
since 1620 a distance equal to about two to three times its
present width. Most of the present dunes are in the form of
"growth rings," and formed in the second half of the nine-
teenth century (Shepard and Wanless, 1971). Analysis of the
frequency distributions of dip angles, azimuths and eleva-
tions of 301 eolian crossbed sets shows that coastal dunes
have a distinctive internal dune geometry. The crossbed
dip angles are mostly low ($\overline{X} = 11.2°$ in all azimuth direc-
tions, at all dune elevations, at all sides of the dunes,
and at all sample localities. Crossbeds with dip angles
of 11-15° yield the most statistically representative azimuth
distributions. The combined azimuths show a statistically
significant correlation with the prevailing northwest, south-
west, and southeast wind directions, rather than with the
dominant northeast storm winds. This association is valid
for crossbed sets at any dune elevation. The azimuth distri-
bution varies between sample localities, with the crossbed
sets tending to dip toward the beach all around the island.

Biweekly field observations and numerous aerial photo-
graphs of Monomoy coastal dunes made during a three-year
period suggest that internal dune geometry is closely de-
pendent on growth of dune vegetation, especially *Marram* grass.
The grass acts as baffles, trapping sand moved by the pre-
vailing winds and producing the vertical accumulation of
sand behind vegetation hummocks on the gently undulatory,
nearly horizontal upper surface of the dunes (Goldsmith, 1972;
1973).

(11) The growth of the recurved spits has resulted in the formation
of several fresh water ponds in the southwest portion of the
island, and which support an extensive floral and faunal com-
munity (including deer). In the mid-1800's one of these
present ponds, Powder Hole, was an extensive harbor with room

FIG. 8.   Aerial View of Coatue Beach, Nantucket Island.

for "14 sail." It can now be walked across without get-
ting one's shirt wet.

The newest pond was formed within two years (1969-1971)
by a new spit growth. Similar to the growth of Nauset Spit,
growth occurs sporadically and rapidly.

The result of these dynamic processes is extensive environ-
mental mixing via overwashing and aeolian sand transported
to the beach from the island interior.

Area G - Nantucket Harbor. Nantucket Island is located 30 km south
of Cape Cod, Massachusetts. Nantucket Harbor, on the north side of
the island, is an elongate lagoon trending approximately northeast-
southwest. The harbor is bordered on the south by Pleistocene moraine
material and on the north and east by the Holocene sand spits, Coatue
and Haulover beaches.

Coatue Beach (Fig. 8) is approximately 10 km long with a maximum
relief of 3m. The topography consists of dune ridges, most of which
are parallel to each other and oriented to the northwest. Six regu-
larly-spaced cuspate spits project into the two southwesterly spits
(First and Second Points), but truncated dune ridges on the four
northeasterly spits demonstrate the erosional form of most of the
shoreline.

Cuspate spits result from a shoreline being reoriented into domi-
nant wave approach directions. They form in elongate lagoons where
the basin shape is a fetch restriction that acts as a selective filter
on the wave spectrum, so dominant wave approaches are at a high angle
to the shoreline. The long axis of Nantucket Harbor is parallel to
two opposing wind directions, the dominant northeast and prevalent
southwest. The longshore processes act in both directions, each erod-
ing sediment from the center of each of the concavities between the
cuspate spits and transporting it to the spit ends, where it is de-
posited as subaqueous bars. The upwind half of each concavity falls
in the lee of the upwind spit, preventing longshore drift before the
center of the concavity.

A comparison of the shoreline of 1781 with the present reveals
remarkably little change in the location of each cuspate spit. The
cuspate spits in Nantucket Harbor are an equilibrium shoreline, as
evidenced by a lack of long-term shoreline changes. There has been
slight erosion in the centers of the concavities, which concurs with
process studies and foredune ridge characteristics. The wind and
waves act through longshore currents as the spit-building process,
which approximately equals the action of tidal currents on the sub-
aqueous bars as the primary erosional process. While material is
eroded from the bars by tidal currents, a greater volume of sand is
returned to the beach at the center of the concavities by ridge-and-
runnel migration than near the spit ends.

The subaqueous vegetation throughout most of the western half of
the harbor is *Zostera marina* (eel grass). This material has spread
from small colonies at the Harbor mouth in the 1940's to its present
extent which dominates most of the western half of the harbor. This
bottom growth inhibits the formation of ridge-and-runnal systems on
the westerly concavities, which may upset the equilibrium of the system.

The eel grass has also stabilized the flood-tidal delta at the harbor mouth. An ebb-dominant tidal channel flanks the tidal-delta to the north, and flood channel to the south.

Nantucket Harbor is bordered on the south by a Pleistocene moraine, and on the north and east by Holocene sand spits, Coatue and Haulover Beaches. At the junction of these spits is a Pleistocene hummock, Coskata, which is a remnant of the source material for Coatue Beach. Immediately south of Coskata are the remnants of an inlet that broke through the beach in 1896. Local fishermen cut through the dunes at the south end of Haulover spit to haul their boats over the sand as a short cut to fishing grounds. The inlet lasted 12 years, and migrated north to the present location flanking the resistant Pleistocene material before closing. While the inlet was open, tidal flow in the harbor decreased, diminishing the scour over the subaqueous bars. This resulted in an elongation of these bars until the inlet closed. This sequence of events demonstrated the trend on cuspate spit shorelines for bar growth to result in harbor segmentation in areas of lower, or zero tidal flow. An example of this can be seen in the fresh water pond between recurved dune ridges at the south end of Monomoy Island.

Cuspate spits are a common feature in the ponds, lakes and bays on Cape Cod and Martha's Vineyard, but the Nantucket cuspate spits are unique for their symmetry and rhythmicity.

Examination of the dune ridges on Coatue Beach show the presence of two unconformities (most evident on Third and Five Finger Points). This suggests that Coatue Beach is the result of at least three phases of accretion: an initial phase of spit growth (presently between the two unconformities); a phase of spit growth to the north, which extended the spit through the pulses of recurves forming First and Second Points; and a phase of accretion to the south, inside Nantucket Harbor. The border between the initial and northern phases of spit growth can be traced to north of Coskata headland, where vegetation changes delineate a change in elevation between the two growth stages.

Great Point, which projects north from Coskata headland, is a low-lying spit that is presumed to have formed as a tombolo. The north end of Great Point lies on a gravelly shoal which is the remains of a hummock similar to Coskata. The influx of sediment from the south has resulted in the formation of large (8 m) vegetated sand dunes. The Great Point Spit is migrating to the southwest over the shallow Pleistocene bench north of Coatue Beach. This migration appears to be less a function of overwash than of accretion by ridge-and-runnel migration on the southwest (landward) side of the spit and erosion on the northwest side.

Area H - Martha's Vineyard. Lying 7 miles west of Muskeget Island, the westernmost part of Nantucket, and 3.5 miles south of Woods Hole at the southwest tip of Cape Cod is the island of Martha's Vineyard (Figs. 1 and 9). Somewhat larger than Nantucket, it is approximately 18 miles from east to west and 9 miles from north to south. Its shape is roughly triangular with its long side on the south, and with

a small triangular appendage (the township of Gay Head) at the western end. The southeastern angle of the triangle is Chappaquiddick, severed from the main island by Katama Bay and Edgartown Harbor.

The Pleistocene geology of Martha's Vineyard is unusually complex. Three morainic systems meet on the western part of the island and within the older moraines, three separate drifts and deposits of at least one interglacial are well preserved. With six recognizable drifts occurring in one small area, probably the most complete Pleistocene section in the United States is found here (Kaye, 1964a, b; Woodworth and Wigglesworth, 1934; Fuller, 1914) starting with Nebraskan and including late Wisconsinan. From the air, however, we can see evidence of three or possibly four.

The lobate early Wisconsinan moraine that makes up the spine of Nantucket continues west to Martha's Vineyard, where it can be seen forming the northeastern side of the island, stretching from Chappaquiddick on the southeast to Vineyard Haven, the town at the northern apex of the triangle. The moraine is somewhat subdued here and attains an altitude of 100 feet at only a few places and, in general, hovers about an altitude of 50 feet. It is not conspicuously bouldery and it lacks the well-developed corrugations found in the central part of Nantucket.

From sea cliffs and excavations, this moraine is seen to consist mainly (but not entirely by any means) of undisturbed stratified sand and gravel. This appears to be superglacial outwash, that is, outwash deposited over a slowly wasting ice front. The outwash plain extends to the south and flying in from the east we see this large outwash plain forming the large central part of the island extending as far as the south shore of the island.

Noteworthy features to be seen from the air

Chappaquiddick - superglacial outwash moraine.

Wasque Point - the southeast tip of the island. Erosion occurs at an alarming rate when the protective sandy beaches are swept away, as they occasionally are. The morainic upland is then eroded at a rate of almost 1 foot per day. The long north-south barrier beach that ties Wasque Point to Cape Poge on the north is fed by strong reversing tidal currents through Muskeget Channel. If the sea is calm, the large arcuate sand apron, or subaqueous delta, at the mouth of the channel can be seen. The surface of this is in perpetual movement. Skiffs Island, a small sandy constriction rising just a few feet above high tide, may be present about a mile southeast of Wasque Point. This island from time to time gets swept away only to reform by build-up of the sandy shoals here.

Cape Poge Elbow is the curiously curved sand spit, projecting west and then south from Cape Poge, at the north end of Chappaquiddick. The mechanics of its formation await study.

Barrier Beach along east side of island, called State and
Edgartown Beaches is a fairly stable feature. Studies (Kaye, 1973)
show no measurable net change in position in the past 200 years.

Lagoon Pond and Lake Tashmoo, two elongate lagoons at north
end of island, are the drowned portions of a looped, or lobate de-
pression that can be seen intersecting the north end of the outwash
plain. This valley shows evidence of ice collapse and resembles a
large river meander in plan.

Outwash plain in the central part of the island slopes about
8 feet per mile southward. A radiating set of shallow dry valleys
that head off to the former ice margin score the surface. The lower
courses of these valleys are drowned and give rise to the numerous
narrow bays or lagoons along the south shore.

South Beach. The long straight east-west south shore of the
Vineyard is marked by barrier beaches across the mouths of the ponds,
or lagoons. Erosion of this shore is appreciable and varies from an
average annual rate of 11 feet on the east to about 6 feet on the
west. Historical documents show that 200 years ago it was possible
to go by boat from one end to the other of South Beach behind a con-
tinuous barrier beach. Since then, the shore has been pushed back
to intersect the outwash plain. The dominant direction of longshore
drift of the sand in the beach is west to east.

The western part of the island consists of three moraines and
the topographic sag of Menemsha Pond. The early Wisconsinan moraine
of the eastern part of the island becomes thin along the northwestern
shore where it is squeezed against the side of the higher and longer
Gay Head moraine. It is found along the entire northwest shore and
its average width is about a quarter of a mile. It would appear that
the larger lobe to the east that built the Nantucket and eastern
Martha's Vineyard moraine. In consequence of this, it was unable to
override the crest of the Gay Head moraine except at the sag in the
moraine at Menemsha (see below).

The largest part of western Martha's Vineyard is the Gay Head
moraine probably dating from Illinoian glaciation. The moraine is
much eroded with two sizeable longitudinal valleys. The surface of
the moraine has been oxidized and eroded. The structure of the moraine
is very distinctive and can be studied in the large, colorful sea cliff
cut into it at the western tip of the island, Gay Head. It is made
up of imbricated thrust plates of pre-existing ground all drifting
north. Individual thrust sheets, or plates, may be as much as 50 feet
thick, but generally are less, and may be a quarter of a mile or more
in length. Somehow the ground over which the ice sheet moved was de-
tached in large plates, moved forward with the ice without significant
internal disturbance and piled up in a great imbricated mass at the
terminus. The major component of the thrust sheets are yellow, white,
red, gray, and black Coastal Plain sediment of Late Cretaceous age.
Also included in the thrust plates, is a highly fossiliferous Miocene
unit and three early Pleistocene drifts with distinctive character-
istics and one fossiliferous interglacial deposit (Kaye, 1964a, b).

Erosion of the Gay Head moraine has etched into relief the more resistant stratigraphic units of the thrust plates. The surface of the moraine is therefore recognizable by the many low ridges that trend parallel to it. Also noteworthy are the large boulders, some of which reach 35 feet across.

Menemsha Pond, separating Chilmark Township from that of Gay Head, was a sag in the Gay Head moraine. The subsequent Early Wisconsinan ice flowed partially through this gap and pushed up an arcuate ridge of sand and clay and some of the older deposits at the margin of its advance. These are exposed in the high cliff (Wequo (Wequobaque Cliff) on the south shore here.

Squibnocket Point is the southernmost point of the island. The cliff exposes very compact peculiarly contorted stratified till interbedded with medium yellow sand and gray clayey silt. The same type of deposits underlie No Mans Land, an island lying about three miles to the south southwest. This type of stratified till and thick sand and gravel crops out on Block Island and eastern Long Island where it is called the Montauk drift. It is very distinctive and unlike other deposits on Martha's Vineyard and is thought to constitute the third morainic system of the Vineyard (Fig. 9).

Gay Head. This spectacular colorful cliff reaches 152 feet in altitude and cuts across the large Illinoian(?) moraine. The colorful beds are all of Coastal Plain origin (Upper Cretaceous-Miocene) and make up the bulk of the cliff. White beds are mostly kaolinitic, medium-coarse sand, some gravel; black beds are lignite and lignitic silt; red is clay. The thrust plates all dip to the north and some of these can be seen from the air (slope wash masks many of these structures). The cliff is eroded largely by large slump-type landslides. Note large one heading up to lighthouse and one near north end of cliff. These can be recognized by sod-covered step-like slices. Early Wisconsinan till in upper part of cliff at north end.
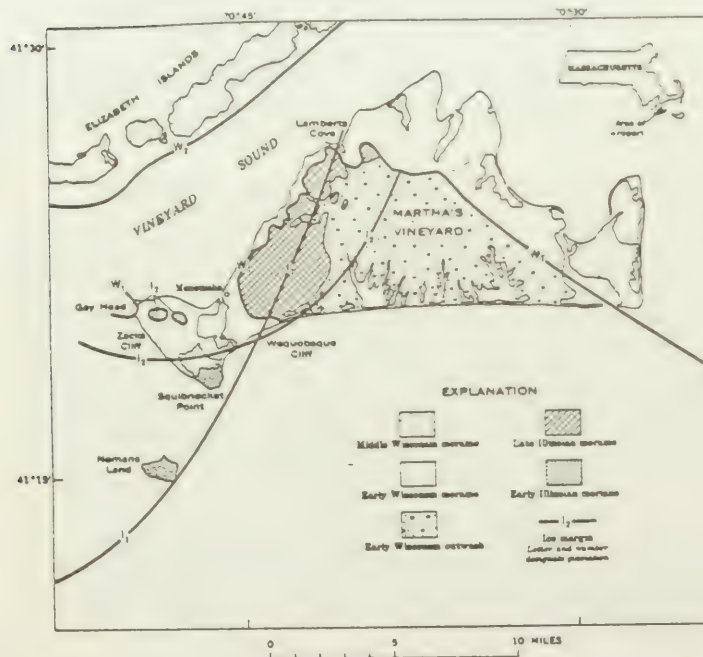
Fig. 9. Map of Martha's Vineyard and surrounding islands, showing inferred ice margins and morains of early Illinoian (I_1), late Illinoian (I_2), early Wisconsin (W_1), and middle Wisconsin (W_2) ice sheets. (After Kaye, 1964b).

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SECTION B
A MESOSCALE VIEW

In Section B of the Cape Cod field trip, we will view the Cape's outer shore from a mesoscale viewpoint. Unfortunately, the guide to the final stop concerning the environmental impact of off-road-vehicles on dune and beach vegetation, was unavailable at publication time; a supplementary handout will be supplied to participants on the trip. The leaders of this section are John J. Fisher, Paul J. Godfrey and Jay E. Leonard. John J. Fisher is principally responsible.

This section of the trip will commence at the visitors center Cape Cod National Seashore, Eastham, Mass. Mileage is logged in the margin by $\frac{xx.x}{y.y}$; where xx.x is cumulative and y.y is between stops. Participants should refer to Fig. 18 for stop locations.

$\frac{0.0}{0.0}$ **Visitors Center, Cape Cod National Seashore Park, Eastham.** This Center is 0.1 mile east of Route 6, at a point 2.8 miles north of Orleans — Eastham traffic rotary ("circle") of Route 6 and 6A. Early arrivers are recommended to visit the center for publications, movies, and special displays showing the general glacial origin of the entire Cape.

The Center's picture window overlooks Salt Pond, a drowned kettle hole, and Salt Pond Bay. In the distance, to the southeast, the beach and dunes visible is that of North Beach, a southerly prograding barrier spit beach enclosing Salt Pond Bay. Nauset Inlet is at its southern end, while the Seashore Park's Coast Guard Beach is at its northern end.

It was the naturalist-philosopher Henry David Thoreau who first studied and wrote of the "Outer Beach" of Cape Cod over 100 years ago. In several trips, he walked the beach from Nauset Inlet to Provincetown. For this "Bi-Centennial" field trip, we will, as it were, be following in Thoreau's footsteps as we make our way north along the Cape Cod Seashore Parks "Great Outer Beach." Note: On leaving the parking lot, turn right, (east) on Nauset Road.

$\frac{0.5}{0.5}$ Nauset Road bears left (north), continue ahead (northeast) on to Doane Road.

$\frac{0.8}{0.3}$ In grove to right (south) is Doane's Rock (Enos Rock), the largest glacial erratic on Cape Cod. It is 45 feet long by 25 feet wide and is 18 feet high, but continues below ground to a depth of 12 feet where it is wind polished to a depth of 5 feet (Oldale, and others, 1968). Volcanic basalt in composition, there are no similar bedrock materials beneath the Cape and some think that the ice sheet eroded and transported it from a belt of volcanic rocks beneath Massachusetts Bay to the northwest (Chamberlin, 1964, 1957). If ice-rafted to this site, the sheet of ice, 5 feet thick would need to be one-half the size of a football field.

$\frac{1.3}{0.5}$ Intersection with Oceanview Road continue ahead (east) to Coast Guard Beach.

$\frac{1.5}{0.2}$ Continue east, then south to entrance to Coast Guard Beach. Park, in parking lot, near north end (entrance).

FIG. 10. Extensive Sea Cliff Erosion at Cape Cod Beach Broading Parking Lot. Erosion Increase may be due to Migration of Fulcrum Point Between Shoreline Erosion and Deposition Segments. Emplacement of Concrete Slabs at Cliff Base did not Stop Erosion. Photo Taken April 1977, Winds From Northeast at 40 mph Causing Sand Drifting Visible on Beach.
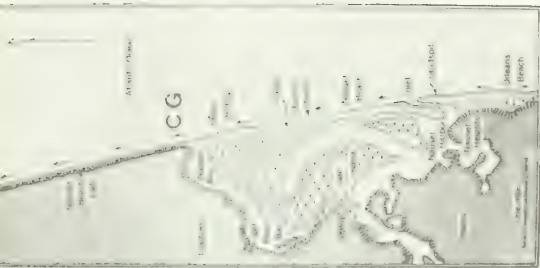
FIG. 11. A. Schematic Indicating Direction of Longshore Drift From North to South Along Nauset Cliff to Nauset Beach. Coast Guard Beach (CG) at Junction (Fulcrum) of these two Segments. Reprinted with Permission from Strahler, 1966. B. Schematic Redrawn by Strahler for Present Guidebook Indicating Change in Drift Direction from South to North as Suggested by New Development Pattern of Sandspit at Mouth of Nauset Inlet (Personal Communication A.N. Strahler, 1975).

1.6 **Stop 1 — Coast Guard Beach.** Extensive wave erosion of both the
—— bluffs (Fig. 10) and the dunes in this recreational area over the
0.1 past several years since about 1970 have been cause for concern.
The question is what coastal mechanism is responsible for this in-
creased erosion? Coast Guard Beach, as part of a spit landform, is
just south of where sea cliff erosion would give way to spit deposi-
tion. A fulcrum point, is the term for this boundary between coastal
erosion and deposition according to W.M. Davis' spit development model.
Perhaps recently there has been a southerly shift of this fulcrum
point, so that former erosion along the sea cliffs, is now shifted to
erosion of the dunes of Coast Guard Beach.

This, however, does not explain increased erosion of the glacial
bluff. It is possible that it is not coastal erosion that is re-
sponsible for this extensive cliff failure, near this southern ful-
crum point, but rather the seasonal spring high water table and the
water-filled kettle hole adjacent to the cliff, just east of the
former Coast Guard Station. During the spring months, (April 1974)
fresh water has been observed flowing from the base of the eroded
scarp. This means that the high water table from the kettle hole
could, by fluidizing the adjacent cliff and beach, allow increased
erosion and this could initiate a wave of erosion moving south and
north in the direction of the longshore current. The relationship
of this southern fulcrum point, a coastal nodal point (longshore
divergence) and the northern fulcrum point to coastal landforms,
beach geometry, sediment distribution and shoreline erosion will be
investigated as we continue northward along the coast.

Erosion in the Spring of 1976, of the dunes and sea cliff ex-
posed the interior section of the deposits and dune sands; which
gave way to the north, to glacial till deposits, overlain by an
organic sand (bay bottom?) and then aeolian cross-bedding. Further
north the till disappears and only aeolian sand is visible. This
indicates that the hill on which the Coast Guard Station stands is
an outline of till. The sea cliffs in the Coast Guard Beach area
and the bluff on which is the Coast Guard Station are part of the
Eastham glacial outwash plain. The sea cliff glacial stratigraphy
have shown beds of till (5 to 10 feet thick) interlayed with beds of
sand and gravel and laminated silts. These various till bodies,
rather than ice-contact deposited, are probably flowtills from the
South Channel ice lobe that existed to the east and which supplied
the general interlobate outwash stratified drift deposits of the
Eastham plain. A fabric study of the long axes of stones in the till
outcropping north of the parking lot indicated a plunge direction to
the west south-west which tends to support a flow till interpretation
of the till beds (Oldale, and others, 1968).

1.8 Leave Coast Guard Beach entrance and turn north (right) on to Ocean
—— View Drive.
0.2

3.7 Continue north on Ocean View Drive, and turn east (right) on Cable
—— Road.
1.9

Stop 2 — **Nauset Lighthouse Parking Lot.** In 1839, three brick light-
houses occupied this site. Continuing cliff erosion toppled all
three into the sea in 1892 and in 1923. Ongoing erosion can be seen
along the edge of the parking lot, where an entire row of parking
spaces has been lost to cliff erosion during the last half-dozen years.

Average rates of cliff erosion along these outer Cape Cod cliffs have been measured as 3 feet per year in the late 1800's (Marindin, 1891), and decreasing to 2-1/2 feet per year in the 1900's (Zeigler, and others, 1964a), and 1.8 feet in the 1970's (Chamberlain and Martin, 1974). Although this erosion supplies sand to the beach below, these beaches do not show a net increase in width, because the eroded material is carried by longshore transport to form the spit barrier beach south of Coast Guard Beach. Figure 11A (Strahler, 1966). From his book on Cape Cod Geology, he diagrams this southern longshore transport. However, in a recent diagram supplied by him for this guidebook (Strahler, 1976, personal communication), he has reversed the direction of longshore drift to the north. He bases this new interpretation on recent changes of the "sandspit" at the Nauset Inlet as shown on the new diagram (Fig. 11B).

The maximum elevation of the Eastham plain on uncollapsed glacial drift in the vicinity of Nauset Light is 80 feet. Eastham plain outwash glacial deposits north of Nauset Light are mostly fine to very coarse sand with few cobbles, in contrast to the silt and boulders present in the deposits to the south. In general, these glacial deposits have a high content of felsic volcanic rocks (Oldale, 1968).

3.8 / 0.1   Leaving Nauset Light Beach parking lot and heading west, continue ahead following Cable Road.

4.7 / 0.9   Just past the high school on the north (right) is the Nauset Road intersection, where Cable Road ends. Turn northwest (right) on Nauset Road.

5.7 / 1.0   Nauset Road ends at Route 6, coming in from the south, turn north (right) and follow Route 6 on the Eastham glacial outwash plain.

8.7 / 3.0   Turn east (right) on road marked Marconi Station with Seashore Park sign.

8.8 / 0.1   Road to north (left) to local school, road to south (right) to Marconi *Beach*, do not take, continue straight ahead (east) to Marconi *Station*.
One approaches the Marconi Station across the Wellfleet plain of Grabau (1897) and Woodworth and Wigglesworth (1934). A glacial outwash plain with a gentle southwestward slope, large entrenched valleys, and numerous kettle holes, it is the oldest, highest, and most extensive of the Cape glacial outwash plains.

9.8 / 0.7   Stop 3 — Marconi Wireless Station. Marconi's first antenna for his wireless station on this spot was destroyed in a gale in September, 1901. Later four towers were erected and began transmitting in January, 1903. Since the placement of the towers, the cliff has eroded 170 feet. Presently the foundation on the edge of the cliff is undergoing erosion. This dramatic example of Cape Cod sea cliff erosion illustrates that while the cliffs continue to erode, the beach below does not increase in width because this eroded material, now, as in the past, is carried by longshore transport south to Nauset Beach and probably Monomoy Island and also north to form the Provincetown spit.
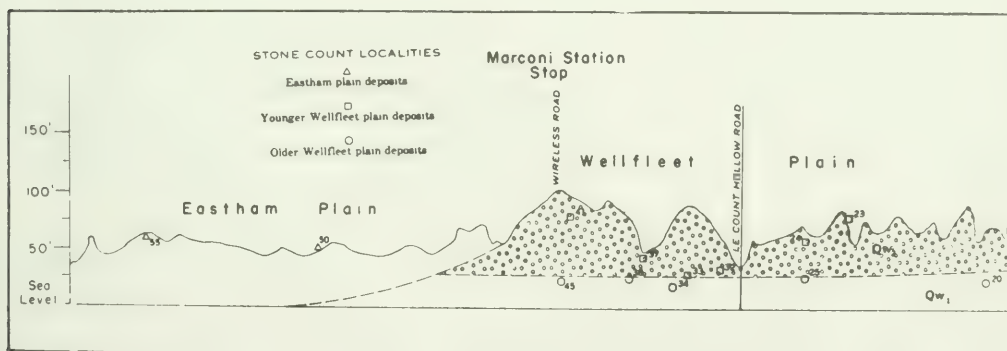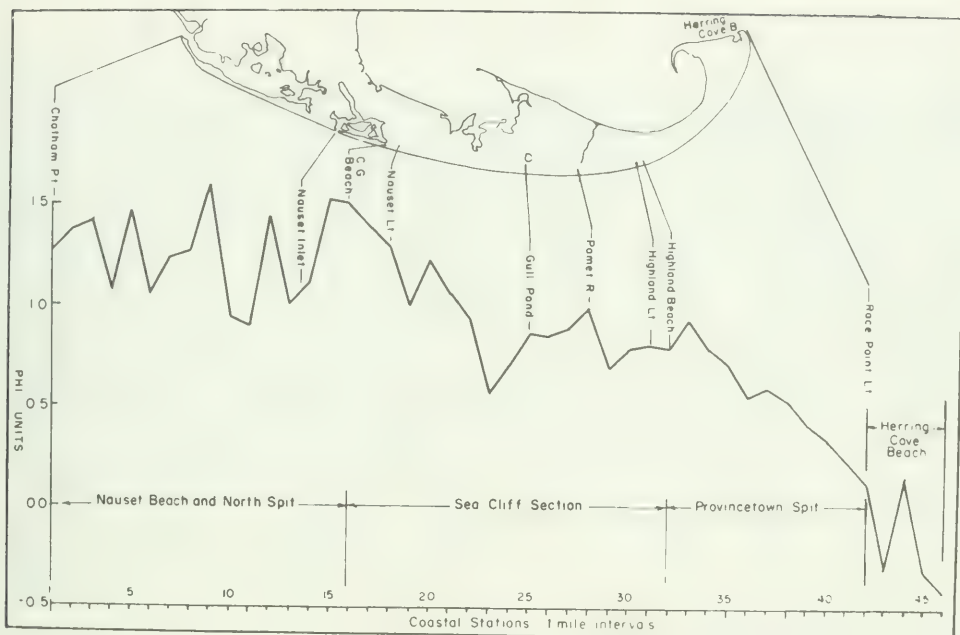
FIG. 12. Regional Pattern of Average (Median) Sediment Grain Size
on Beach Foreshores of the Outer Cape Shoreline, Collected in October
Representing Summer Beach Deposition. Size Varies from Medium Sand
(2.0 to 1.5 φ) to Very Coarse Sand (0.0 to -0.5 φ) with Medium Sand
Size Along Nauset Beach and Spit Increasing to Medium-Coarse Sand in
Sea Cliff Region, the Expected Source Area. However, from the Sea
Cliff Region North Towards the Provincetown Spit, the Average Sand
Size *Increases* Rather than Decreases in the Supposed Direction of
Longshore Drifting (from Fisher, 1972).

FIG. 13. Glacial Stratigraphy of Sea Cliffs Along Marconi Station
Area Showing Relationship of Eastham Plain Deposits, Younger Well-
fleet Plain Deposits and Older Wellfleet Plain Deposits. Sequence
Determined from Field Relationships and Stone Counts of Differing
Pebble Lithology in Different Plain Deposits. View is to West,
North to Right (from Oldale, 1968).

The nodal point or that point at which this net flow of sand changes from north to south along this coast has not been well-established. Hartshorn, and others (1967) suggested this dividing line was somewhere near the center of the eastern Cape Cod shoreline. This might put the location just north of the Marconi Station. Strahler, (1970, personal communication) had suggested that a migration of this nodal point southward from the suggested mid-cape locations might be responsible for the apparently increasing cliff and beach erosion in the Nauset Light and Coast Guard Beach areas. To study this problem of nodal location, a seasonal beach study program that covered the entire Cape Cod National Seashore coastline from Provincetown to Chatham was conducted by Fisher and students (Fig. 12). By the seasonal sampling of beach sands, the measurement of beach geometry, and the collection of meteorological and sea state parameters, the quantification of the qualitative observations made by Davis (1896), Woodworth and Wigglesworth (1934), Schalk (1938), and Strahler (1966) concerning: (1) seasonal longshore transport patterns, (2) seasonal location of the nodal point, and (3) seasonal location of fulcrum points of equilibrium between erosion and deposition is attempted.

Field studies were made in October 1970, to represent the end of the "summer beach" of accretion and in April 1971, at the end of the "winter beach" of erosion. At both times, the sampling period was confined to two or three days in an attempt to negate any effect of changing wind and wave conditions. Forty-six stations were established at one mile intervals from Provincetown to Chatham, with several sediment samples collected at each station just above the mid-tide mark on the foreshore ("reference point" of Bascom, 1951). The plot of the median grain size of the combined foreshore beach samples of the summer beach (October), is presented in Fig. 12. Median grain size is greatest, not along the cliff face beaches, as might be expected, but north along the Provincetown spit and are in the coarse to very coarse sand range (0.5 ϕ to -0.5 ϕ). Along the cliff section median grain size is within the coarse to median sand range (1.5 ϕ to 0.5 ϕ); whereas, along the southern beaches (North Spit and Nauset Spit), the median grain size falls completely within the medium size (1.0 ϕ to 1.5 ϕ). There is a greater variability of grain size trend along this southern beach section than along the central cliff face beaches. The least variation in grain size trend actually occurs along the Provincetown spit beach proper.

From the Marconi Station overlook, one can see that 500 feet to the south is the contact between this Wellfleet plain and the lower Eastham plain of the Nauset Light area. The scarp on the west, also between the Wellfleet and Eastham plains is "thought to be an ice-contact slope developed when part of the South Channel lobe occupied the site of the Eastham plain deposits" (Oldale, and others, 1968). One-third the way down the cliff face is the contact between the younger and older Wellfleet outwash plain glacial deposits (Fig. 13). The older unit (Qw_1) is composed of fine to very coarse gravelly sand. However, within this unit are beds and lenses of pebble and cobble gravel, fine to very fine sand and clayey silt. Boulders, tens of feet in diameter are common and some pebbles in the deposit are wind-polished. Large scale deltaic foreset bedding as well as planar bedding, tabular and cut and fill crossbedding and current ripples suggest both glaciolacustrine and glaciofluvial depositional

environments, respectively. Reworked fossil material includes
carbonized wood and shells of Pleistocene age, fossiliferous sand-
stone cobbles of Eocene age, silicified wood of Cretaceous or Teri-
tary age and fish teeth (Oldale, 1968).
      The younger second unit of the Wellfleet deposit (Qw_2) overlies
the older Wellfleet deposit and occurs in a more limited area from
just north of Cohoon Hollow to just south of the Marconi Station.
It is similar to the older Wellfleet deposits except that the boul-
ders and clayey silt beds are not present. Planar, tabular, scour
and fill crossbedding and current ripples suggest a glaciofluvial
depositional environment (Oldale, 1968). These glacial stratigraphic
sedimentary units are similar along most of the Cape Cod cliffs and
these can be considered as typical of the units at other stops except
where indicated otherwise.

10.8 Continue ahead (west), road to south (left) if followed, leads 1.5
1.0   miles to Marconi Beach.

10.9 Route 6, turn north (right).
0.1

11.6 Cross Blackfish Creek. Blackfish Creek is within a wide tidal marsh
0.7   valley that is the result of the drowning of the lower reaches of a
      proglacial outwash meltwater stream that flowed from the northeast
      across the Wellfleet plain surface and emptied into the proglacial
      Cape Cod Bay lake. This is one of a series of similar relict ero-
      sional valleys extending north along this section of the Cape. Their
      gradients in the Wellfleet plain are between 38 to 87 feet per mile,
      almost four times the gradient of the plain itself (Hartshorn, and
      others, 1967). Most of these valleys are straight, narrow and steep-
      walled and graded to below present sea level.

11.7 Turn east (right) onto LeCount Hollow Road which follows the extension
0.1   of this proglacial valley from Blackfish Creek towards the edge of
      the sea cliff. These valleys, called "pamets" after the Pamet River
      further north, have heads which terminate both within the plains, or
      others, like LeCount Hollow extend completely across the Cape from
      the bay to the cliffs above the ocean. The various "hollows" or
      lower sags along the Cape Cod sea cliff are where these "pamets" ex-
      tend completely to the cliff edge. Along LeCount Hollow Road are
      numerous kettle holes which indicate that the valleys were cut before
      the ice blocks melted, evidence that the valleys were formed during
      late-glacial times.

12.1 To the south (right) is Wireless Road.
0.4

12.5 Intersection to north (left) with Ocean View Road, continue ahead
0.4   (east).

12.7 LeCount Hollow, the seaward extension of the Blackfish Creek pamet,
0.2   the hollow or "sag" between the sea cliff representing a proglacial
      valley "gap." Do not stop, unless instructed, turn around in parking
      lot, which is a Wellfleet Town Beach. On the beach below, the sand
      sediment size has been steadily increasing since Coast Guard Beach
      (Fig. 12) where there, the average beach sediment size was that of
      medium sand (.3 mm), it has been increasing in size northward along

the shoreline and along the next few stops it is between the medium
and coarse sand size (0.5 mm). This sediment size change will con-
tinue to *increase* rather than *decrease* to the north towards Province-
town Spit. Even along this cliffed highland area, beach sediment
size *increases* in a regular pattern to the north. This is the basic
coastal geology "mystery" of the Cape's Outer Shoreline.

12.9 Turn north (right) onto Ocean View Road. From LeCount Hollow Road,
0.2 Ocean View Drive road heads north along the edge of the sea cliff on
the younger Wellfleet pitted outwash plain surface. Numerous small
dry kettle holes occur in this plain.

13.8 Parking area to each (right). The sediment size on this beach is
0.9 coarser than the trend along the sea cliff beaches (Station 23,
Fig. 12). Its average size is about 0.7 mm while the average size
of the trend in this area is 0.5 mm. This difference may not seem
significant but reference to Fig. 12 does show how this 0.2 anomaly
stands out. The coarser size is possibly a reflection of a local
source.

14.6 Road to east (right) leads down to Cahoon Hollow, another lesser sag
0.8 in the cliff edge. No distinct pamet channel leads off to the west
(left), but a number of ponds, Great Pond and Dyer Pond, may indicate
the line of former subsurface ice, in such a channel. The ice then
melted leaving this line of kettle hole ponds to indicate its course.

14.8 Road moves off the younger Wellfleet Plain and onto the older, lower
0.2 Wellfleet Plain.

15.7 Continue following Ocean View Road, which bears off to east (right),
0.9 to Newcomb Hollow Road.

16.1 **Stop 3a — Newcomb Hollow Beach.** This coastal sea cliff "hollow" is
0.4 again a gap developed by shore erosion of the headward section of a
proglacial outwash stream channel, a pamet. On the beach below, the
average sand sediment size has decreased slightly (Station 25, Fig. 12),
but still follows the trend of increasing size northward. A dynamic
morphologic/sedimentologic model suggests that from these erosional
sea cliffs, longshore drift should be moving both north and south to
form the Provincetown Spit and Nauset Spits, respectively. The *in-
creasing* beach sediment size to the north, appears in contradiction
to this model, since grain size should *decrease* in the direction of
drift, especially from the erosional sea cliffs to the depositional
spits. Seemingly, there is only one other situation similar to this,
Chesil Beach Dorset, a spit beach along the coast of England, King
(1974). King could offer no reasonable explanation for the reverse
size sorting on the Chesil spit beach. The concept of diverging long-
shore drift directions is related to coastal nodal points or nodal
zone. The nodal point is that point along a shoreline where the di-
rection of longshore drift changes "180 degrees." It has been well-
documented along the northern New Jersey coast, near Manasquan Inlet,
next inlet north of the well-known Barnegat Inlet, where the long-
shore deposition patterns against the numerous groins and jetties
along the shoreline, make location of this reversal of drift direc-
tions fairly easily. In contrast, along the Cape Cod outer shore,
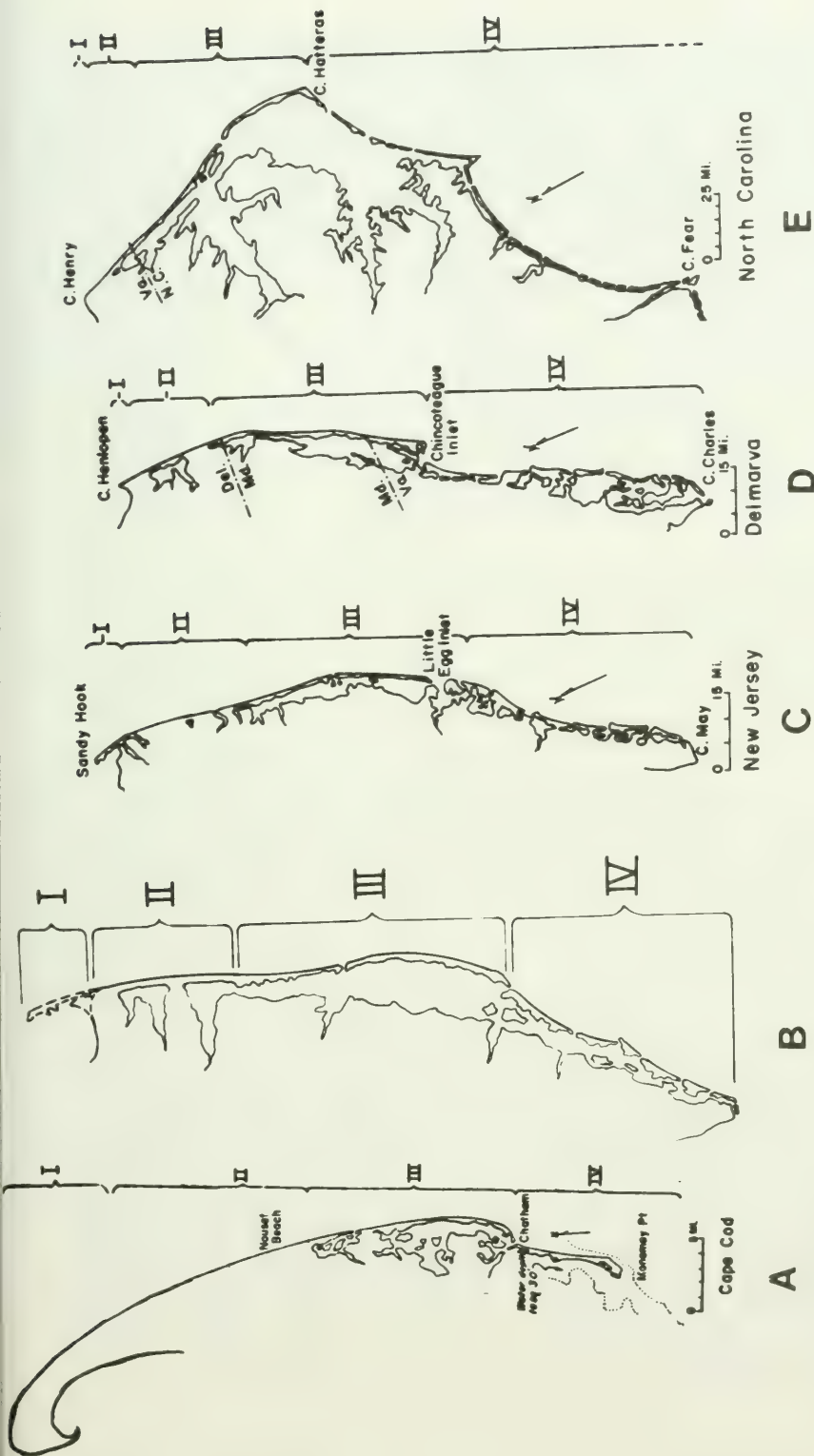
FIG. 14. Analog Relationship of Cape Cod Coastal Morphologic Units
(A) to Fisher's Model of Morphologic Shoreline Compartments for
Certain Barrier Islands in General (B, from Fisher, 1967) and as
Applied by Analog Analysis to Atlantic Coast Barrier Islands (Fisher,
1969 in Swift) Including the New Jersey (C), Delmarva (D) and
North Carolina (E) Barrier Island Chains. Coastal Morphologic
Units as Follows: I - Spit or Cape; II - Mainland with Drowned
River Valleys and Baymouth Barriers; III - Linear Barrier Islands
with Few Inlets and Open Lagoon; and IV - Offset Curvilinear Barrier
Islands with Numerous Inlets and Tidal Marsh Filled Lagoons.

there is not a single groin or jetty and so the location of the
nodal point or zone must be inferred by other means. A possible
location of this shoreline's nodal point, by a simplified wave
vector analysis suggests that the Newcomb Hollow/Cahoon Hollow
section may be the general area. The general dominant waves for
the outer Cape shoreline is from the east-northeast and a vector
from this direction is perpendicular to a tangent to the present
shoreline here at Newcomb Hollow. Vector wave analysis is more
complicated than this example, but it illustrates the approach.
When considering this nodal/fulcrum point aspects of the de-
velopment of the Cape Cod coastline, it can be related to other
Atlantic coast shorelines (Fig. 14). First of all, the Cape Cod
coastline can be subdivided into four morphologic subunit shore-
line compartments (A, Fig. 14). There is the northern Provincetown
spit (I), the sea cliff, Truro-Wellfleet-Eastham headlands (II), a
barrier spit segment that is convex seaward in plan, the Nauset
Beaches, both north and south (III) and a barrier spit segment that
is concave seaward in plan, Monomoy Island and Handkerchief Shoals
to the south (IV). These Cape Cod coastal morphologic shoreline seg-
ments or compartments have a direct relationship to a model that
Fisher (1957) developed previously for certain barrier island chains.
On Fisher's model for these barrier island coastlines, (B, Fig. 14),
the first morphologic shoreline segment is a spit or cape (I, B,
Fig. 14). The second segment is a mainland shoreline with or with-
out baymouth barriers across drowned river valleys (II, B, Fig. 14).
The third segment is a concave-convex in plan (a-b), offset to each
other, with numerous inlets and lagoons with much tidal marsh sedi-
mentation. Fisher later showed that this model could be applied
directly to the barrier island chain shorelines of the Atlantic
coastline (Fisher *in* Swift, 1969). The classical barrier island
shoreline of New Jersey (C, Fig. 14) can be shown to possess these
model shoreline segments, as can the *Delmarva* barrier island shore-
line (D, Fig. 14). Finally, the last barrier island shoreline, south
of Chesapeake Bay, the Virginia-North Carolina "Outer-banks" barrier
island chain (E, Fig. 14) also has these segments on perhaps a slightly
larger scale than the previous two barrier island coastlines (note the
scale of C and D compared to that of E in Fig. 14). Kraft and others,
(1972), in a study of the subsurface Holocene stratigraphy of the
Delmarva coast was able to apply the "Fisher model" to paleo-
sedimentary environments.
Therefore, the development of the Cape Cod shoreline also bears
directly on the origin of these barrier island coastlines, since
Fisher (1973, 1969, and *in* Saxena and Klein, 1971) suggested that
the morphologic and stratigraphic features of certain Atlantic bar-
rier islands indicate that they develop due to longshore drift on
shorelines of submergence and not on a shoreline of emergence. Thus,
if the Cape Cod coastline with its nodal headland zone and its north
fulcrum spit and south fulcrum spit, can also be shown to be related
in its shoreline segments (A, Fig. 14) to those on "Fisher's barrier
island model" (B, Fig. 14) and to typical barrier islands (C, D, and
E, Fig. 14), then this is evidence by analog that the barrier islands
developed by primarily longshore drifting, as has the Cape Cod coast-
line.

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The glacial units in this area are the Older Wellfleet plain deposits of clayey silt at the bottom of the section working up through silt and sand to medium to coarse sand to medium to coarse sand at the top at 48 feet (Oldale, 1968). Overlying this is 2 to 3 feet of medium-to-coarse dune sands, an irregular deposit averaging about 500-1000 feet wide just back from the cliff edge along this eastern shore. These eolian deposits are probably the result of wind action immediately after retreat of the ice sheet. As we leave Newcomb Hollow, the road follows the pamet for 0.3 mile.

16.5 Ocean View Road from the south (left), continues ahead (west) on
0.4 Gross Hill Road.

17.2 Gross Hill Road continues west, bear northwest (right) on Gull Pond
0.7 Road.

17.3 Gull Pond to the north (right), one-half mile diameter and 66 feet
0.1 deep is one of the large kettle hole ponds on the outer Cape. It lies directly on the axis of the pamet leading from Newcomb Hollow and suggests that buried ice blocks help localize the outwash stream pamet channels.

18.6 Gull Pond Road follows the south side of the pamet in which flows a
1.3 stream west to the Herring River. Upon reaching Route 6, turn north (right). Sign at road intersection "Newcomb Hollow Road."

19.4 Cross Herring River, another pamet system, heading in a number of ket-
0.8 tle hole ponds (Herring Pond, Slough Pond, etc.) to the east (right) and ending in a tidal marsh at sea level to the west (left).

20.3 Round Pond, well-developed kettle hole pond on west (left).
0.9
20.4 Great Pond, on east (right) is a kettle hole pond, that forms the
0.1 head of a pamet, Lombard Hollow, that drains to the west (left).

21.9 Cross over Pamet Road South, careful turn coming up. Quick look to
1.5 east (right) for view of pamet.

22.0 Turn east (right), then turn south (right), and east (left).
0.1
22.1 This now puts you on Pamet Road South, heading east. To the north
0.1 (left) is Pamet River, the largest pamet on the Cape and the type locality of this geomorphic feature which is found along the outer Cape. Pamet is defined as a glacial outwash stream channel on an outwash plain, with the original stream now gone and a relict channel remaining with perhaps an unfit stream. In some cases, as in Cape Cod, at its lower edge, along Cape Cod Bay, a tidal stream or estuary is present, due to drowning of the relict channel by a transgressing sea. The pamets have heads which terminate within the outwash plains, often at a water-filled kettle hole or the channel extends completely across the outwash plain to the ocean. Where this relict channel reaches the ocean and where there are eroding sea cliffs, the head has been eroded away, and the channel itself creates a sag or gap in the cliff edge, referred to locally as "hollows."

The presence and location of these hollows are important locally, since they are often the only means of reaching the beaches below from the top of the sea cliffs along the outer Cape.

Numerous kettle holes along many pamets suggest that the valleys were cut before the ice blocks melted and that the ice forming these kettle holes was buried below the surface and were not ice blocks on the surface. This also suggests that the pamets formed during the later stages of the glacial retreat. At Pamet River, the largest pamet on the Cape, the valley is wider (0.5 mile) and deeper (50 feet minimum) than any other pamet on the Cape, there may have been more dead ice present. The question arises then, to what extent is this wide valley due primarily to fluvial meltwater or the buried ice collapse? Along the Pamet River pamet channel valley walls there are what appear to be incomplete terraces, if these are terraces, the question arises as to whether they are fluvial terraces, indicative of extensive meltwater deposition and erosion or perhaps they are kame terraces, and if kame terraces, they then suggest a greater influence of ice rather than water on the development of these larger pamets.

<u>22.9</u> Straight ahead (east), intersection with Collins Road.
0.8

<u>23.8</u> Stop 4 — **Ballston Beach**. Park here for excellent view, down valley,
0.9 south/southeast of Pamet River pamet. This pamet may also have reached to the ice lobe's edge, where Ballston Beach at the ocean edge forms a low hollow that is actually longshore drifted beach sands and wind action developed dunes. Since the Pamet River, from its harbor to these dunes, here, are both at sea level elevation, this pamet was once considered as a possible site for the Cape Cod Canal. On the beach itself, the average size of the sands are slightly finer than those 5 miles north and south of this site (Station 28, Fig. 12). The increase in the finer fraction is probably supplied from these dunes backing the beach. Upon leaving the parking area, continue ahead (north) onto North Pamet Road going west.

<u>24.1</u> On the north (right), there is a well-formed almost circular kettle
0.3 hole, just about 150 feet in diameter.

<u>24.3</u> Again, to the north (right) there is a larger, elongated kettle hole,
0.2 that has, in the past, been ditched and drained on its north side as a cranberry bog.

<u>24.6</u> North (right) again a cranberry bog and the road climbs up what may
0.3 be an incomplete erosional terrace and onto the Wellfleet plain.

<u>25.5</u> At first intersection of "cloverleaf," turn right and immediately
0.9 right onto Route 6. There may be a short stop to view the pamet, to the east towards the ocean, and west to the bay.

<u>27.4</u> On the east (right) is Long Nook Road, again another pamet, which
1.9 leads some 1.3 miles to the North Truro town beach, which was infamous a couple of years ago, as Cape Cod's nudie beach.

<u>28.4</u> East (right), South Highland Road.
1.0

<u>28.9</u> Leave Wellfleet Outwash Plain (150-175 feet above sea level) and
<u>0.5</u> enter onto the lower Truro Outwash Plain (50-75 feet above sea
level).

<u>29.1</u> Turn east (right) onto South Hollow Road. Immediately to south
<u>0.2</u> (right) are town wells. All of Cape towns get their water from a
ground water supply. The highly porous and permeable outwash gla-
cial deposits are excellent ground water reservoirs and all surface
water goes almost immediately underground. There are no streams on
the Cape, except for some tidal "streams" and the water level observed
in most kettle hole ponds is at the local water table level.

<u>29.4</u> South Hollow Road, leaves lower Truro Plain and enters onto contact
<u>0.3</u> between highest Wellfleet Plain to south (right) and intermediate
height, Highland Outwash Plain (100-125 feet above sea level) to
north (left).

<u>29.8</u> Turn north (left) on South Highland Road. Sand quarrying ahead in
<u>0.4</u> "undifferentiated sand deposits of uncertain origin, chiefly valley-
bottom deposits" (Oldale, and others, 1967).

<u>30.2</u> Turn east (right) onto "Highland Light Road." To south (right) is
<u>0.4</u> Highland Golf Course. Road is on Highland Outwash Plain.

<u>30.5</u> **Stop 5 — Highland Light.** Follow trail south (right) to overlook.
<u>0.3</u> Please do not enter onto lighthouse property.
          The wave-cut cliffs at Highland Light are remnants of a once
more extensive land mass to the east. The original extent of the
Cape Cod offshore land mass can be estimated by multiplying the
average rate of cliff erosion of 3 feet per year (Zeigler, 1960)
by the length of time the sea has been at its present level. Curry's
sea level rise curve (1965) indicates that about 3,500 years ago sea
level was close to the present level and has been rising slowly but
steadily since then. These figures suggest that the original Cape
Cod shoreline extended some 2 miles offshore (3,500 × 3 = 10,500 feet).
Shaler (1897) claimed that "slope extension" indicates that this
original shoreline could not be less than one half mile or more than
four miles. Davis (1896) suggested that the "greatest retreat of the
original shore to the present shore" was about 2-1/2 miles based on
fulcrum retreat and reconstructed the initial shoreline on this basis.
He also suggested that this erosion would have occurred within the
past 3,000 years based on average rates of erosion. Erosion still
continues along these cliffs, both by wave erosion below, where at
high tide, the water reaches the cliff base and at the top where land-
slides occur. To the north (left) of the overlook, fissures or "mole-
tracks" are often visible, paralleling the cliff from 5 to 10 feet
back from the edge. These are fractures, the beginning of the fault
on which a landslide block fails. In September 1972, a 200 square
foot section of this cliff failed and 10,000 cubic feet of sediment
was deposited on the beach below (Giese and Giese, 1974). The average
size of sediment on the beach itself is not unusually coarse (Station
29, Fig. 12) being between medium and coarse sand. In fact, the finer
material of this station and those north and south is probably due to
an input from the finer silts that make up the "blue clays" of Truro.
Highland Light, 120 feet above the beach, is situated on the Highland
Plain (Qh), a small triangular area, bordered on the south by the

50 foot higher Wellfleet plain (Qw, Fig. 18). These Highland Light glacial deposits are among the most well-known of the various Cape Cod glacial features. While Grabau (1897) was the first to describe the Wellfleet and Truro plains, the Highland plain, (lower than the Wellfleet plain to the south and higher than the Truro plain to the north) was first recognized by Wilson (1906).

The stratigraphic section of the Highland plain deposits exposed in the sea cliff at Highland Light has been known for many years (Woodworth and Wigglesworth, 1934) although there are now differences in interpretation as to age and depositional environments. At the base of the cliff, 30 to 70 feet of iron stained coarse sand to pebbles and cobble gravel is overlain by 0 to 45 feet of gray clay and silty clay, which is then overlain by 15 to 40 feet of yellowish-gray, fine to medium grained sand. This upper sand unit is ripple-laminated, however the upper section of the clay unit is contorted into rolls and faulted and contains "clastic" dikes which penetrate into the upper sand unit. Similar deformation features, probably due to slump during deposition, are found within the main body of this clay unit (Hartshorn, and others, 1967; Oldale, and others, 1968).

In the past, these three glacial units were correlated with the Jameco Gravel, Gardiners Clay and Jacob Sand on Long Island (Woodworth and Wigglesworth, 1934). The silt-clay unit, in particular, has been correlated with the Gardiners Clay by numerous early workers (Fuller, 1906, 1914; Woodworth and Wigglesworth, 1934; and Hyyppa, 1955). Hyyppa pointed out the marine character of the clay on the bases of diatoms; but, since the type Gardiners Clay on eastern Long Island is considered interglacial in age, it does not seem likely that this late Wisconian age glacial clay on Cape Cod is correlative with the Gardiners Clay.

Oldale, and others (1968) show that, in general, these Highland plain glacial deposits were laid down in a body of water (marine?), dammed by the Wellfleet plain to the south, the Cape Cod Bay ice lobe to the west and the South Channel ice lobe to the east. South Channel ice is shown to be the source of the sediments by the westerly slope of the surface of the plain and stone counts within the deposits itself (Koteff, and others, 1967). The clay unit interfingers with the sand unit, as it pinches out to the south, while it is truncated by erosion to the north. This stratigraphic relationship is evidence of both its local and glacial character and thus again, could not be correlative with the Long Island interglacial Gardiners Clay.

30.8 At South Highland Road, turn north (right), leaving the Highland Out-
0.3   wash Plain.

30.9 On Highland Road, (sign indicating "To Route 6 and 6A") turn west
0.1   (left).

31.7 Just before the Route 6 overpass, turn south (left) onto the approach
0.8   and then north (right) onto Route 6.

32.0 Road east (right) leads to Head of Meadow Beach, a "hollow" leading to
0.3   the shore.

33.3 Stop 5a — Pilgrim Springs - Head of Meadow will be made. Leaving
1.3 Route 6, the road to Pilgrim Spring passes over the Truro plain.
Truro plain is the most northern of the glacial outwash plains of
the outer Cape and is about 50 feet lower than the Highland plain.
Less ice collapse and meltwater erosion features are found on this
plain. Truro plain deposits overlie the Highland plain deposits
with an unconformable contact, indicating that it is younger than
both the Highland and Wellfleet deposits. These Truro sediments
are primarily fine-grained, yellowish-gray flat-bedded ripple lami-
nated sand with scattered pebbles and cobbles. No till was found,
although a till-like material is found in the cliff near Highland
Light. Its origin is uncertain, it may be a landslide, ice rafted
or a turbidity flow, and has been called "diamicton" (Flint, and
others, 1960a, 1960b). In addition, steeply dipping deltaic foreset
beds are found in the Truro deposits (Hartshorn, and others, 1967).
        From the parking lot, a short walk along the Pilgrim Spring
trail leads to a relict or "fossil" sea cliff above the "Head of the
Meadow." The meadow referred to, is the salt meadow below that,
separates the Truro plain from the Provincelands spit that has grown
from a junction to the south along the sea cliffs. This junction on
the initial Cape Cod shoreline must have been southeast of the present
junction at Head of the Meadow beach. Davis (1896) pointed out that
as this spit grows by accretion and the cliff retreats by erosion,
there is a neutral point of "fulcrum" of no change along the shore-
line; but, with time, on the initial seaward Cape Cod shoreline, this
fulcrum will shift toward the spit as the cliff erodes.
        Below the Pilgrim Spring overlook, this cliff, above the present
meadow, was originally a marine sea cliff above the open ocean until
the first Provincetown spit was built from the Highland Light area
to the south (right).
        Sand dunes visible to the north, on the outer shoreline of this
spit are parabolic or "U" in shape with the open end of the dune facing
into the dominant prevailing wind which along this section is from
the northwest. Parabolic dunes generally develop where there are
large amounts of sand together with some vegetation, in this case,
beach grass and various low salt tolerant shrubs such as bayberry.

33.7 Route 6 drops down the face of the former marine sea cliff "High Head,"
0.4 which was open to the sea until spits growing from the ocean and bay
side isolated it from the sea.

34.1 High Head Road to north (right) follows the base of this relict sea
0.4 cliff and leads to a trail over the dunes on the spit.

34.7 Route 6 follows along a spit enclosing Pilgrim Lake to the north
0.6 (right). This shallow water lake (depth 3-5 feet) was originally a
salt water bay, into which the Pilgrims sailed to find fresh water
before crossing Cape Cod Bay to find their settlement at Plymouth.
The inlet originally at this point, closed in 1869 and its tidal
delta is visible to the north (right).

35.8 North (right) at the western end of the lake is the Mt. Ararat dune
1.1 field parking lot.
        The climb up the sand trail from the parking lot to the top of
Mt. Ararat is only 50 feet, but the loose sand makes the climb dif-
ficult. From the dunes, the view to the southeast illustrates the

concept of High Head as an ancestral marine cliff with the Province-
land spit, now covered by parabolic dunes, growing from a fulcrum
along its present oceanic cliffed shoreline. Perhaps the earliest
spit that was formed, reached from High Head on the east, passed
through this Mt. Ararat area and continued west to form the land on
which Provincetown is situated.

   Dunes in the Mt. Ararat area are not as recognizably parabolic
as those on the far side of Pilgrim Lake, and are more open or semi-
circular in shape with their central axis oriented to the northwest.

36.7 Dunes migrating from the north (right) onto the highway. The dunes
0.9   have developed from the sand of relict spit ridges. Under the
      dominant northeasterly winds, these sands move across the highway
      at a rate of 12 feet per year.

37.8 Road intersection, at traffic light, turn north (right) onto Race
1.1   Point Road, sign indicates "Provinceland." From Route 6, Race Point
      Road heads northeast towards the ocean. The road passes through a
      forested lowland that lies between the ancestral Provincetown spit
      and the older of the more recognizable relict beach spits. This
      lowland area, about one-half mile wide, perhaps represents a past
      change in the rate of sea level rise, with the sand forming a wide
      foreshore or nearshore but not a series of narrow spit frontal ridges.
      Other, less likely factors, might be change in sediment supply or
      meteorological patterns.

38.2 Just before the road enters the relict beach spits, a trail to the
0.4   west (left) leads through Beech Forest.

39.0 Road to east (right) leads to the Seashore Park Ocean View Shelter.
0.8   If time is available, we may stop there. Ocean View Interpretive
      Shelter is directly on what is perhaps the third relict spit ridge.
      To the south, on perhaps the oldest spit ridge, can be seen the Pil-
      grim Monument, together with the intervening forested lowland of the
      Beech Forest area.

39.2 Road to west (left) leads to Herring Cove. Continue north on Race
0.2   Point Road with relict spits and intervening ridges curving off into
      the distance. From this vantage point it is easy to visualize each
      of the relict ridges as "lines of growth." To the northeast and
      north, a wide trough between the most recent relict ridges begins
      to appear, and in the view to the northwest along Race Point Road,
      we see that the Provincetown Airport occupies this wide trough.
      This trough probably represents a very wide relict beach formed be-
      fore the frontal or foredune ridge on the growing spit, much like
      the wide beach in front of present-day Race Point Beach. Undulations
      in Race Point Road as it heads northwest towards the beach indicates
      the ridge and trough topography of these relict spits.

39.8 Stop 6 — Race Point Beach. The most recent of these growing spit
0.6   beaches is, of course, present-day Race Point Beach. Race Point
      Beach usually exhibits "abrupt day-to-day changes" and measurements
      of seasonal beach changes have ranged from a maximum elevation of
      over 18 feet above mean low water to a minimum of 3.5 feet (Zeigler
      and Tuttle, 1961). Offshore from Race Point Beach there is a fairly
      permanent longshore bar, Peaked Hill Bar. The dynamics of this bar

are probably responsible for most of the abrupt changes along this beach. Peaked Hill Bar actually begins tangent to the beach at Highland to the east and extends westward, terminating at Race Point. This bar is offshore, a distance of 2,000 feet, and as the shore makes a sharp turn to the south at Race Point, the Peaked Hill Bar also turns, but gradually merges into the shoreline.

Between Peaked Hill Bar and the Race Point Beach, observations indicate that at times the sand moves onto the beach as a series of giant ripples or bars. Sometimes these smaller bars are also transverse to the beach as they migrate along the shoreline (Zeigler and Tuttle, 1961).

The coarsest beach sediment size on the Cape Cod outer beach is found here at Race Point Beach. The average sediment size is almost that of very coarse sand (Stations 40 to 42, Fig. 12). If this sediment is transported by longshore drifting from the highland cliffs to the south, one would expect the sediment size to decrease away from the source area. The beach sediments along the southern part of the Cape, Nauset Beach, do decrease in size in the direction of longshore drift, but not here to the north in the Provincetown spit shoreline. Changes in the direction of longshore drifting were thought to occur some 18,000 and 6,000 years ago when sea level was lower. At that time, sand eroded from the highlands, further offshore, was moved from the north to the south, but as sea level rose, and Georges Bank, to the east, was submerged, more waves could reach the Cape from the east and southeast and the Provincetown spit could begin to form (Zeigler, and others, 1965). That reversal in littoral drift direction occurred many years ago and does not seem to explain the reverse trend in present-day beach sediment size along the Provincetown Race Point beaches.

SECTION C
A MICROSCALE VIEW

In Section C, we will view the microscale coastal processes and resulting geomorphic structures and bedforms occurring on Coast Guard Beach and Nauset Spit. Transportation will be by four-wheel drive vehicles. The leaders of this section are Stephan P. Leatherman and Paul J. Godfrey.

Barrier beaches, islands and spits, are common features along the Atlantic and Gulf Coasts of North America. Their exposed position and low physiography make them highly vulnerable to severe storms. With the present eustatic rise in sea level (Hicks, 1972), these barriers are presently being eroded (National Shoreline Study, 1971). Overwash, the transport of sea water and sediment across the island during storms, is a major component of the barrier islands response to these high energy conditions. In addition, overwash processes may be important to the possible landward migration of these islands.

Overwash is defined as the continuation of the uprush over the crest of the most landward (storm) berm (after Shepard, 1973; Leatherman, 1976). The resulting deposit is not subject to reworking on the active beach by normal wave and tidal action.

FIG. 15.   Nauset Spit Washover Fan with Sand Deposited Over High Salt Marsh.
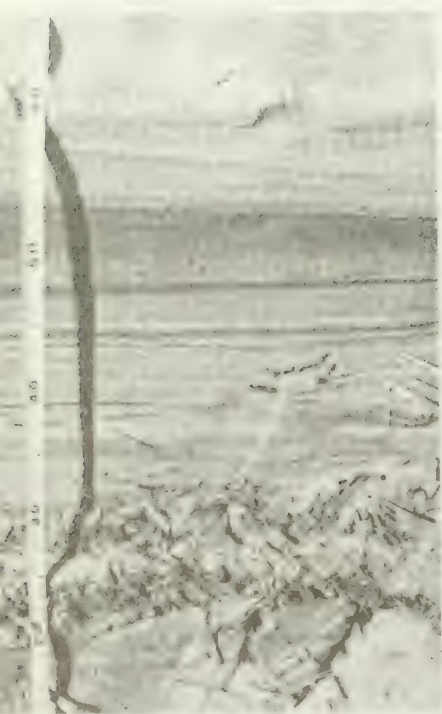
FIG. 16.   Overwash Sedimentary Sequence from a Single Storm Event.

FIG. 17.   Eroding Peat Outcropping on the Beach Face in Front of a Washover.

The surges transport sediment to the eolian flats or marsh, depending on their magnitude and the island's width. The narrow breach through the dune field is referred to as the throat or neck. The fan is that portion of the washover where the deposit is allowed to flare due to the lack of horizontal constraints. Broad washover flats, as contrasted to discrete fans with flanking barrier dunes, generally mark the position of previous inlets.

Overwash is important in terms of its ecological and geological implications. Godfrey and Godfrey (1972) found that overwash is partly responsible for creating new marshes and providing nutrients to the salt marsh system. The *Spartina alterniflora* that colonizes the new sediment has been shown to be more than twice as productive as older marshes in North Carolina. Therefore, overwash is deemed significant on the short-term basis.

The geological implications of overwash are more difficult to evaluate. After 26 months and seven discrete overwash events, there was no net gain of material on the back-dune area for the washover fans on Assateague Island, Md. (Leatherman, 1976). One of these storms, the December 1, 1974 northeaster, was one of the largest storms to affect these shores in the past 25 years from wave hindcast analysis. The prevailing northwest wind transported the bulk of the material back onto the beach face before it could be colonized by the Spring growth. Therefore, the washover fan is viewed as a temporary reservoir for the eventual redistribution of the material by the wind. Overwash appears to be relatively unimportant on the short-term basis, at least for the area cited. This viewpoint agrees with the Corps of Engineers position that island maintainence by overwash processes is probably only significant within the context of a geologic time frame (Corps of Engineers, 1974).

Coast Guard Beach parking lot in Eastham marks the end of the eroding glacial material and the beginning of Nauset Spit, a coastal accretionary landform. The National Park Service built Coast Guard Beach parking lot and bathhouse in 1964. Shoreline recession threatens to close off this area, and the bathhouse remains unprotected due to the rampant erosion. The sand derived from these eroding cliffs has served to create and nourish Nauset Spit and Monomoy Island.

The segment of shoreline between the parking lot and Nauset Inlet (Fig. 10) is also eroding as marked by narrow beaches, wave-scarped dunes and numerous washover fans. A large breach in the frontal dunes occurred in 1972 as a result of a severe northeaster. Sand was deposited to a depth of several feet over the *Spartina patens* salt marsh as a fan (Fig. 15). Much of this sediment was derived from erosion of the dune itself, the remainder supplied from the beach and shoreface. To a large degree, the *Spartina* has not recovered, much of the area remains bare, except for some colonization by American Beach grass (*Ammophila*). Once the grass becomes established, it acts as a baffle to the eolian-transported sand, and a small dune is now forming. This revegetation pattern is unlike that found along the North Carolina shoreline (Godfrey, 1970).

A trench, dug into the overwash sand in the throat section, revealed the characteristic horizontal laminations (Fig. 16). Measurements taken at Assateague Island during storm conditions showed that the overwash surges move across the threshold at high velocities due to the initial momentum imparted to the surge by the breaking wave. Maximum instantaneous velocities of 9 feet per second at 2 inches from the bottom for a one foot surge were recorded at Nauset Spit for the March 16-17, 1976 northeaster. Froude numbers indicate that subcritical to critical flow regimes persist, resulting in parallel bedding (Leatherman, 1976).

Between 20-30 cm. there exists a mat of debris. This vegetal material is concentrated as the prevailing northwest winds strip off the sand, transporting large quantities of the overwash sediment back to the beach. Therefore, this debris represents an old surface and marks the position of the base of the new material. At 50-54 cm. there exists a concentrate of heavy minerals, principally ilmenite and garnet. Previous analysis of storm deposits illustrated that this concentrate is negatively skewed and therefore hydraulically-lagged (Leatherman, 1976). The heavy mineral band represents the height of storm surge when the waves were allowed to advance closer inshore before breaking and the surges reached their maximum flow conditions. The heavy sand layer is found at approximately mid-section in a fresh overwash deposit, but subsequent (post-storm) wind erosion is much in evidence (note small wind shadow dunes in Fig. 15). As one proceeds southward, the laterally spacing between fans decreases until a barrier flat is encountered over 500 meters north of the inlet. This area was planned off by a temporary inlet in 1972 that moved southward until it merged with the present day inlet. Overwash processes and eolian transport, acting principally in opposite directions, tend to keep this area low and non-vegetated.

At the first distinct fan north of the washover flats, a large section of salt marsh peat is exposed at low tide following storm-induced beach erosion (Fig. 17). The peat is underlain by very coarse sand which is poorly size-sorted, suggesting it is of inlet origin. This peat material is being dated by the U.S.G.S. - Woods Hole, and further investigations are currently in progress. Figure 17 also shows the seaside scarping of the barrier dunes and small wind shadow sand accumulations tailing toward the East.

Nauset Inlet is anomalous in its behavior since it is migrating northward even with a predicted net southward littoral drift. The flood tidal delta is left stranded with this movement, and it serves as a substrate for marsh development and expansion. The ebb tidal delta is well-defined by the position of the breakers seaward of the inlet.
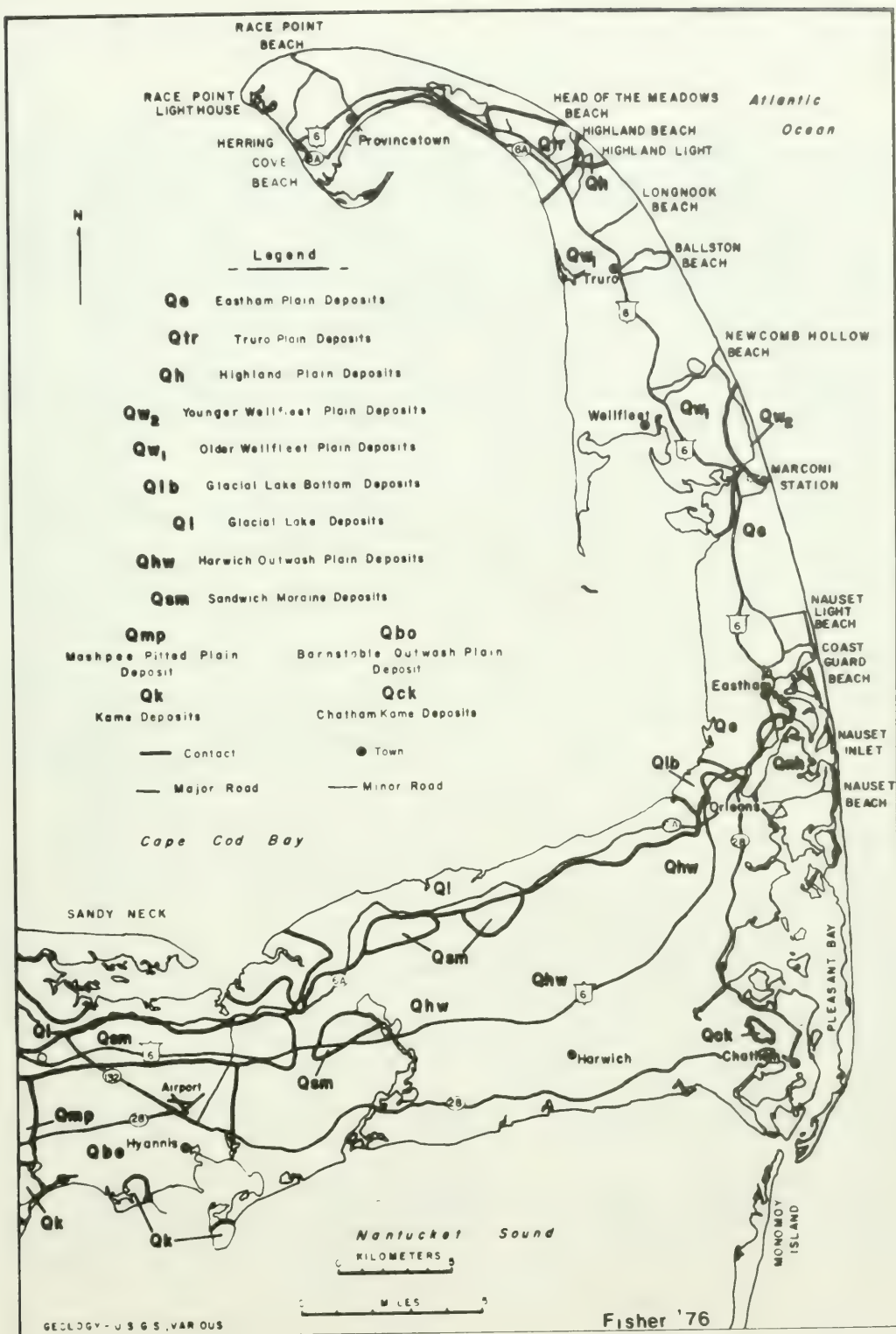
FIG. 18. Generalized Geological Map and Section B Route Map of
Cape Cod.

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PLUTONIC SERIES IN THE CAPE ANN AREA

by

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Plutonic rocks of Cape Ann ranging from gabbro through granite to feldspathoidal syenite were described by Washington in 1899 (p. 463) as belonging to the "petrographical province of Essex County, Massachusetts".   Later workers, although usually recognizing the close relationship of these rocks, have divided them into a number of named units, i.e., Nahant Gabbro (Clapp, 1910; equivalent to Salem Gabbrio-diorite, LaForge, 1932), Salem Gabbrio-diorite (Clapp, 1910, 1921; Emerson, 1917, Laforge, 1932); Beverly Syenite (Clapp, 1910, 1921; Emerson, 1917), Cape Ann Granite (Warren and McKinstry, 1924, equivalent to Quincy Granite, Clapp, 1910, Emerson, 1917), Squam Granite (Clapp, 1910; related to granite of Cape Ann, Emerson, 1917), Cherry Hill Granite, and Wenham Monzonite (Toulmin, 1964). Note only have distinct units been named, but they have been ascribed widely different ages because of their intrusive relations. However, recent field and petrographic study (Bell and Dennen, 1972), spectrochemical analysis of some of the same minerals from the mafic and salic phases (Dennen, 1972), and studies of major- and minor-element chemistry (Survant, University of Kentucky, Norton, 1974, and Norton and others, 1975), make it apparent that Washington's (1899, p. 464) assessment of these rocks as belonging to a petrographic province, i.e., "... a region of igneous rocks which possess in common certain characters, structural, mineralogical, or chemical, and in which the characters may vary continuously from one end to the other of the series of rocks represented" is correct and that separation into named stratigraphic units is unwarranted. The term "plutonic series in the Cape Ann area", as proposed by Bell and Dennen (1972) is, therefore, used herein, those named units having long historical standing or showing clear cut intrusive relationships being retained as facies.

The various rocks of the Cape Ann area (Fig. 1) are as-
semblages of similar minerals in differing proportions. Feld-
spars are typically greenish with a greasy luster; microcline
microperthite dominates in the salic phases and is a minor con-
stituent of the related diorite. Mafic facies contain both a
pinkish titaniferous pigeonite and a pale-green augite; iden-
tical augite is sparsely distributed in the salic phases.
Hornblende shows continous chemical variation, especially mark-
ed for Fe/Mg, from early to late phases; the amphibole (hast-
ingsite) is always iron rich, and in phases more salic than
gabbro, tends to be soda rich as well. Biotite of similar ap-
pearance is found in both mafic and salic facies, being a more
common salic rocks constituent towards the west and southwest.

Mafic Rocks

Hornblende diorite, in part of the Salem Gabbro-diorite of
Emerson (1917) and Toulmin (1964), having a variable but often
well-oriented fabric and veined with pink felsic stringers,
borders the salic rocks of the Cape Ann pluton to the north,
west, and southwest. It underlies Marblehead Neck, the west-
ern part of Salem Neck, and Great and Little Misery, Eagle,
Coney, and Great Haste Islands and Gray Rock in the Salem-
Beverly area and forms a band between the Ipswich and Eagle
Hill Rivers in the Ipswich quadrangle. A large pendant is
found in the south-central part of the Ipswich quadrangle.
Large and small dioritic xenoliths are sparsely distributed
throughout the salic rocks, and distinctive gabbro porphyry
and anorthosite inclusions, characterized by large (as much
as 10 cm) white-weathering red-purple labradorite phenocrysts,
are found in several areas in the pluton--along Route 128 for
1.3 km southwestard from the Grapevine Road interchange, at
the Gloucester terminus of Route 128 and 1.1 km to the west,
and for about 6 km along the northwest shore of Cape Ann,
notably on Davis Neck.

The Salem Gabbro-diorite facies of the "Cape Ann plutonic
series" is a medium- to medium coarse-grained, texturally
variable, mottled black and greenish-white ferrohornblende-
biotite diorite containing variable amounts of augite, pigeo-
nite, and quartz. The rock consists of 55-65 percent plagio-
clase as twinned andesine-oligoclase (zoned crystals An_{35} and
An_{20}) and untwinned albite or oligoclase, 5 percent potash
feldspar, 1-5 percent quartz, 0-25 percent pale-green augite,
0-10 percent pinkish titaniferous pigeonite, 10-30 percent
green pleochroic iron-rich hornblende, 0-10 percent reddish-
brown biotite, and 1-5 percent opaque minerals as scattered
granules and exsolved blades in pyroxenes. Accessory apatite,
zircon, and sphene as grains and rims on opaque granules are
also present. Chlorite, iron oxide, and calcite are commonly
found as alteration products. Mafic minerals are always some-
what poikilitic and commonly occur in zonally arranged aggre-
gates that represent a reaction series from augite to biotite,
magnetite granules being dispersed throughout the aggregate.

Biotite occurs as irregularly scattered flakes. The feldspars
are pale gray-green and have a greasy luster. The fabric is
irregular and uneven. The rock is often brecciated and cut
by salmon-pink felsic stringers.

Salic Rocks

Gray-green, white- to brown-weathering phaneritic salic
rocks ranging in composition from quartzose alkali granites
through alkali quartz syenites to alkali syenites and feld-
spathoidal syenites are the principal rocks of Cape Ann. They
are generally unfoliated and have an uneven hypidiomorphic to
subporphyritic texture. Crystal sizes range from 0.5 to 1 cm
for most facies, but the syenites are more variable and local-
ly very coarse grained.

Syenites having crystal sizes of several centimeters,
sometimes containing nepheline and sodalite (the pulaskite and
umptekite facies of the Beverly Syenite of Washington, 1898,
1899; Clapp, 1921) form extensive masses along the Beverly-
Manchester shore and the adjacent harbor islands close to the
contact of the salic rocks with the Salem Gabbro-diorite.
Medium-grained trachytic syenite makes up Bakers Island where
it is a cognate igneous breccia containing ovoidal clasts.
Coarser trachytic syenite is also associated with the coarse-
grained facies and is found as dikes intruding it.

The Cape Ann Granite facies is predominantly an unfoliated
fine-medium to coarse-grained (0.3 to 1.5 cm) leucocratic al-
kali granite to alkali quartz syenite. Ranges and medians of
the principal minerals are: microcline microperthite 58-85
(63) percent, *plagioclase (An_{6-12}) 0-22.5 (2.8) percent, quartz
0-41 (24) percent, ferrohornblende 0.1-17 (4.5) percent, bio-
tite 0-3.2 (0.8) percent, opaque minerals 0.2-7.5 (1.0) per-
cent. Augite is occasionally present. Accessory minerals in-
clude sphene, ziron, apatite, fluorite, allanite, magnetite,
and ilmenite. Feldspars in the unaltered rock are pale green-
gray, have a greasy luster, and weather to a faintly pinkish
tan or white. Potash feldspar, the dominant mineral, is unual-
ly microcline micropherthite but sometimes is homogeneous mic-
rocline; albite or oligoclase is present in minor qualtities.
Quartz is glassy, shows weak strain shadows, and contains dust-
size inclusions. Feldspar and quartz occur as large single
grains and grain clusters partly to completely surrounded by
finer grained interstitial quartz and feldspar. Ferromagnesian
minerals are variable in amount and occur as ragged clots, wisps,
single subhedral crystals, and zonally arranged reaction aggre-
gates. Augite is colorless to pale green as a core partly or
completely surrounded by pale-green amphibole, darker green
hastingsite, and reddish-brown biotite; magnetic granuales are
scattered throughout the reaction aggregate. Isolated crys-
tals and clots of soda-iron amphibole, biotite, or both are
common. The rock typically has an uneven granitoid to subpor-
phyritic fabric and often shows cumulate texture.

The Beverly Syenite facies principally consists of unfol-
iated medium-grained granitoid rocks, whose composition, except
for lack of quartz, is closely similar to that of the Cape Ann
Granite facies. These syenitic rocks are usually texturally
variable, often show small pegmatitic patches, and are rarely
flow banded. Textural extremes, essentially restricted to
the Beverly-Manchester shore and islands of Salem Harbor, in-
clude very coarse grained (2-5 cm) granitoid and ophitic phases,
pegmatites, and medium-grained trachytic rocks (Bakers Island),
which often contain nepheline and sodalite.

Fine medium-grained monzodiorite (?), equivalent to the
diorite of Shaler (1889) and the Squam Granite of Clapp (1910),
forms an irregular ellipsoidal 1.3- x 4- km body trending N.
30°E. from Little River to Ram Island, Gloucester, and is
found widely scattered as inclusions throughout the other salic
facies. Field relations place this rock as post-Salem Gabbro-
diorite and pre-Cape Ann Granite facies.

The Squam Granite facies is a fine- to fine-medium-grained,
medium-gray granite which weathers brown and has a highly sil-
iceous appearance. It is a texturally and mineralogically var-
iable rock whose texture ranges from hypidiomorphic or allo-
triomorphic granular to subophitic and subporphyritic. Plag-
ioclase is present as anhedral to subhedral zoned and unzoned
equant or bladed grains variable in amount and composition,
ranging from less than 5 to more than 40 percent of the rock
and from about An_{30} to An_{55}. In subporphyritic varieties,
phenocrysts are more sodic than groundmass plagioclase (An_{30}
vs. An_{40}). The potash feldspar may be orthoclase, microcline,
or microcline microperthite either alone or in combination
and ranges from a minor to the dominant constituent. Grains
range from anhedral to subhedral, equant to bladed, and fresh
to highly sericitized. Zoning is fairly common. Anorthoclase
is often present as an accessory mineral. Quartz is in slight-
ly strain-shadowed equant or interstitial glassy grains and
makes up 15 to 30 percent of the rock. Ferromagnesian minerals
compose from less than 5 to moe than 50 percent of the rock.
Poikilitic ferrohornblende and red-brown biotite are the prin-
cipal dark constituents and are present in roughly equal quant-
ities. Pyroxene (pigeonite) is rare and typically occurs as
unreacted cores. Accessories include apatite, zircon, opaque
minerals, sphene, allanite, and monazite.

Lynn Volcanic Complex

Flow rocks, agglomerates, and pyroclastic rocks of the Lynn Volcanic Complex (Clapp, 1910, 1921; Emerson, 1917; La-Forge, 1932) are found on Marblehead Neck and outer islands in Salem Harbor. These rocks are usually dark purplish-red to black felsites, originally glassy but now devitrified, dense, and always porphyritic to some degree. Petrographic examination and semiquantitative spectrochemical analysis indicates that they are rhyolites. Closely spaced jointing yielding small rhombohedral blocks is characteristic. Thin layering is often conspicious, contorted, and generally has steep dips. Massive felsites to the south are succeeded northward by agglomerates and thinly flow-banded rocks; inclusions of massive felsites in the more northerly units suggest that the units top northward. The contact of these extrusive rocks with rocks of the Cape Ann pluton is not exposed and is probably a fault. Basalt porphyry and diabase dikes, believed to originate from the Salem Gabbro-diorite facies, cut the volcanic sequence, notably on Cat Island, whereas rhyolite dikes similar in composition and appearance to the massive and banded volcanic rocks cut various facies of the "Cape Ann plutonic series." If these tenuous associations are correct, the Lynn Volcanic Complex represents an extrusive facies of the Cape Ann pluton, as believed by Clapp (1921) and Toulmin (1964).

Dikes

The rocks of the Cape Ann pluton are cut by many dikes, which are closely related to the emplacement of the rocks of the "Cape Ann plutonic series." The Cape Ann Granite facies is the source of aplitic and pegmatitic dikes, usually narrow and having irregular and gradational boundaries and typically a simple mineralogical makeup. White-weathering aplites, pegmatites, and aplite-pegmatites are found only within the granite and syenite facies, whereas pink felsitic dikelets are characteristic of the Salem Gabbro-diorite facies. A wide variety of medium- to coarse-grained trachytic and pegmatitic syenite dikes arise from the Beverly Syenite facies and are principally found in the Salem Harbor area, where they cut syenitic and less commonly dioritic and granitic rocks. Massive, banded, and porphyritic rhyolite dikes, which may be feeders of the Lynn Volcanic Complex, cut Cape Ann Granite from Manchester to Rockport. Many mafic dikes having granular, ophitic, and porphyritic textures (plagioclase phenocrysts) cut all the rocks of the area. They are widely distributed and locally may constitute most of the exposed rock. Many of these mafic dikes have been disrupted by movement of incompletely consolidated salic magma and are now seen as isolated angular blocks separated by unfoliated granite. As these dikes must have been emplaced before consolidation of the enclosing salic rocks, a local comagmatic source such as an incompletely

salinified, possibly immiscible subjacent gabbroic phase is
indicated.

Genetic History

Barker and others (1975) have presented a consistent model
for the genesis, emplacement, and composition of a suite of
igneous rocks of which the "Cape Ann plutonic series" is pro-
bably representative. Geochemical studies of Cape Ann Granite
by Buma and others (1970) support the model.

In simple outline, a mantle-derived convecting olivine ba-
salt magma reacts with potash-poor lower crustal rocks to yield
first a liquid of iron-enriched gabbro, then alkali diorite,
and lastly quartz syenitic composition. In turn, these liquids
react with rocks of the intermediate crust to form large vol-
umes of granitic magma. Residua rich in ferromagnesian min-
erals and calcic plagioclase and differentiated by crystal
settling are continuously generated.

Characteristically, the silicic rocks of representative
intrusive groups* are intrusive into older cratonic rocks under
anorogenic conditions as ring- or ovoid-shaped masses (removed
by erosion on Cape Ann) and associated with complex groupings
of gabbro, diorite, syenite, anorthosite, and minor aplite
and pegmatite.

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*identified by Barker and others (1975) as rocks of Pikes Peak,
    Colo., Cape Ann-Peabody area, Mass., younger granites of
    Nigeria, Rapakivi massifs of southern Finland, and syenite
    of Kungnat, Greenland.

Field relations of the exposed part of the "Cape Ann plu-
tonic series", indicate that emplacement began with the intrus-
ion of mafic magma, which crystallized to form the Salem-Gab-
bro-diorite facies. The wall rocks, as indicated by inclusions,
were a series of mafic volcanic rocks (?) and thin-bedded sed-
imentary rocks, probably mainly siltstones. Locally, a dis-
tinctive gabbro porphyry-anorthosite roof phase is preserved
in the later salic intrusions. This earlier intrusive pulse
was closely followed by the emplacement of a thin (+ 1000-m
sheet) of salic magma separated (at depth?) from a common re-
servoir. Settling of feldspar crystals from the salic magma
onto the subjacent diorite, possibly in response to lowered
pressure accompanying the extrusion of the Lynn Volcanic Com-
plex (Toulmin, 1960), caused the early formation of coarse-
grained granitoid and trachytic feldspathoidal phases. Con-
temporaneous crystallization without crystal settling may have
generated the Squam Granite facies along the Annisquam River.
Crystallization of the salic magma continued, possibly coupled
with wall-rock assimilation and crystal settling, as shown by

the common cumulate texture, in which the interstices between subhedral feldspar grains are filled by quartz and hornblende. Differentiation and reaction resulted in a large-scale rough layering from quartz-poor basal to quartz-rich upper phases.

Magnetic and gravity evidence (Joyner, 1963; Kane and others, 1972) indicate that the salic rocks of the Cape Ann pluton are in the form of a rather thin sheet floored by a denser and more magnetic body, probably Salem Gabbro-diorite. The presence of pendants and xenoliths of Salem Gabbro-diorite in the salic rocks suggests that the salic rocks may be an unroofed sill.

Intrusion of the salic magma caused local brecciation of incompletely consolidated Salem Gabbro-diorite, and many mafic dikes were squeezed from it to penetrate the salic mush, where they were chilled by the slightly cooler granite and then disrupted by its continued movement. Extrusion-intrusion of this kind combined with mafic-salic reactions may account for some of the considerable composition variability of the Salem Gabbro-diorite facies.

At some point in the consolidation history, most probably early in the emplacement of salic material, felsic stringers derived from the salic magma cut the dioritic rocks and provided the matrix for cognate breccias in the gabbro-diorite.

Summaries of geochronologic data by Fairbairn and others (1967) and Fairbairn (1971) suggest a convergence of the absolute ages measured by various workers to 450 m.y. (late Middle Ordovician boundary) for the salic rocks of Cape Ann. Zartman and Marvin (1971) gave an age of 450 $\pm$ 15 m.y. for the Salem Gabbro-diorite facies. Geologic evidence suggesting a younger age for the "Cape Ann plutonic series" is based upon the lack of regional metamorphism and its petrologic similarity to Devonian and younger plutons in New Hampshire, Maine, and Nova Scotia.

Faults

Topographic lineaments, magnetic interpretation (Barosh and others, 1974; Barosh, oral communication), occasional offset contacts, and some cataclasis indicate that the Cape Ann area has undergone extensive faulting. The general sense is an easterly continuation of the imbricate thrust zone of eastern Massachusetts (Bell, 1967), the principal faults being northeast-trending high-angle thrusts, west over east, which usually have a dextral strike-slip component.

To the north, the bedrock in the Ipswich quadrangle is divided by two major faults trending northeast into alternately metamorphosed and unmetamorphosed terranes. Several essentially parallel lineaments marking probable faults cross the northwestern part of the Marblehead North quadrangle, the eastern part

of the Gloucester quadrangle, and the Rockport quadrangle.
These faults appear to interact in a complex way with a group
of north-northeast-trending faults through the eastern part
of the Marblehead North quadrangle and the western part of
the Gloucester quadrangle.

Metamorphism and alteration

Metamorphic effects in the extensive area occupied by
rocks of "Cape Ann plutonic series" are restricted to garnet-
grade thermal metamorphism of metasedimentary inclusions and
the development of porphyritic texture in the granite adja-
cent to inclusions. Postconsolidation hydrothermal activity
has locally produced a color change in the feldspars of rocks
of the Cape Ann pluton from their normal gray-green to pink
and has chloritized the ferromagnesian minerals.

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BEDROCK GEOLOGY
CAPE ANN, MASS.

Scale approx 1" = 2mi

Dennen 76

Fault
Lithotype boundary
② Field trip station

LV Lynn Volcanic Complex
2/3 Cape Ann Granite facies   3 > 25% quartz
1   Beverly Syenite facies } 1-8 2
     Squam "Granite" facies }   1 < 5% quartz
+   Salem Gabbro-diorite facies
▲   mafic metavolcanics

GEORGETOWN
SALEM
IPSWICH
MARBLEHEAD
NORTH
GLOUCESTER
ROCKPORT
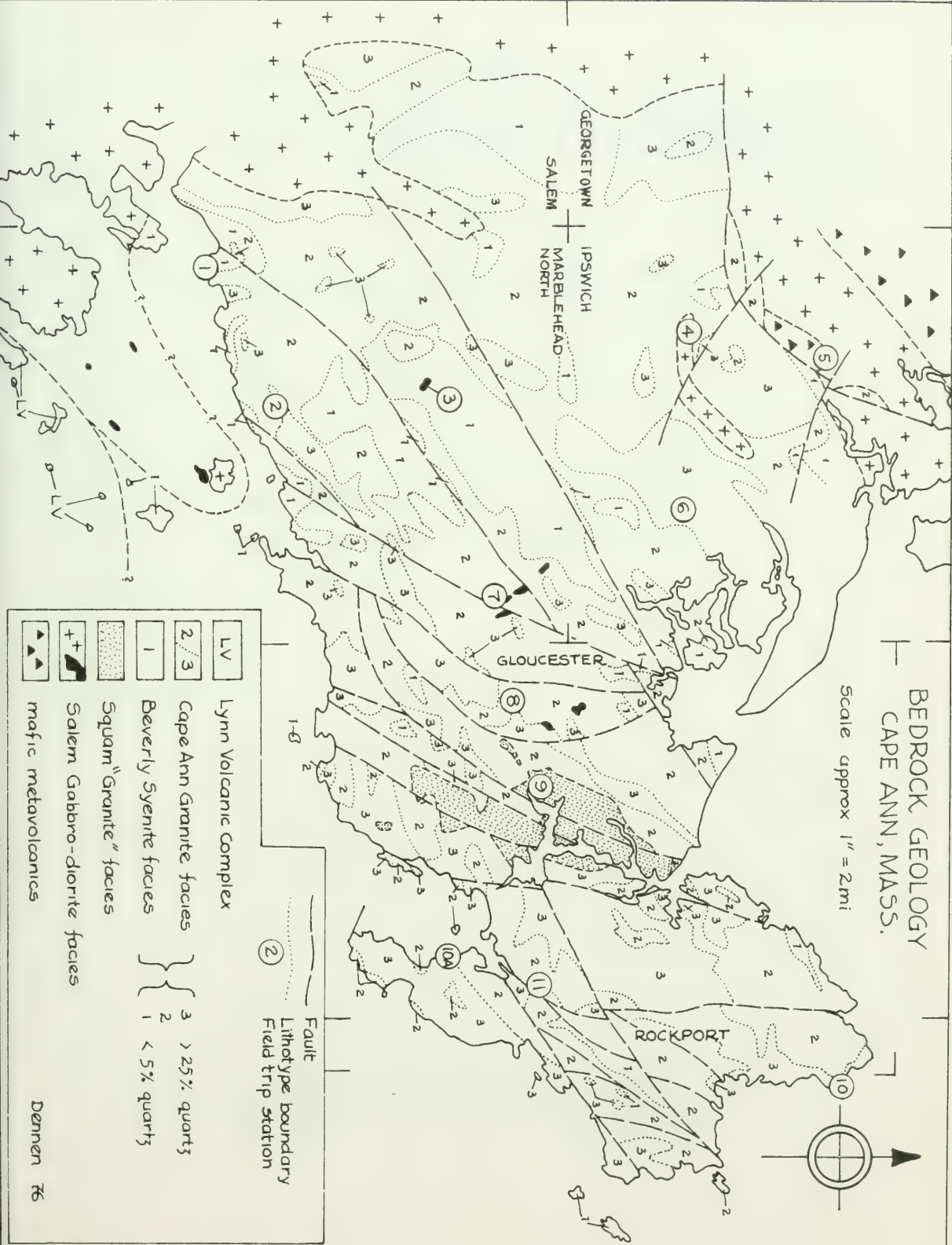
ROAD LOG

Starting point is parking lot of Lynch Park on Woodbury
Point, Beverly, Mass. (Marblehead North 7-1/2-minute
quadrangle).

Mileage

Cum.	S/S	
		STOP 1. Beverly Syenite facies, inclusions, mafic dikes. Salem Gabbro-diorite facies at Marblehead to south.
0	0	Road log begins. Travel north on Ober St.
0.6	0.6	Jct. with Rte. 127, turn R, follow Rte. 127 east.
2.8	2.2	STOP 2. Church at jct. of Rte. 127 (Hale St.) and Haskell St., Beverly Farms. Quartzose Cape Ann Granite facies, some cataclasis. Follow Haskell St. (L turn at church).
3.8	0.5	Jct. Haskell St. and Grapevine Rd., turn L (north).
5.2	1.4	Rte. 128 overpass.
5.9	0.7	STOP 3. Large inclusion of Salem Gabbro-diorite facies.
6.5	0.6	Jct. with Rubbly Rd., turn R (north).
7.2	0.7	Cross Essex St. (Rubbly Rd. now Woodbury St.). Browns Hill to west is a drumlin. From here to Stop 4, the route is across glacial till and outwash which supports an active "horsey" area-- Myopia Hunt Club, polo, etc.
7.8	0.6	Jct. with Bridge St., turn L (west).
8.7	0.9	Jct. with Rte. 1A (Bay St.), turn R (north).
9.2	0.5	Enter Ipswich 7-1/2 minute quadrangle.
11.2	2.0	STOP 4. Metasedimentary and mafic metavolcanic rocks in west end of large pendant. To east, pendant dominantly Salem Gabbro-diorite facies. Appleton Farm to west continuously worked since 1630.

| 13.3 | 2.1 | STOP 5. Ipswich Common.
Contact breccia, clasts of mafic metavolcanic rocks and possibly Salem Gabbro-diorite facies in matrix of quartz-poor Cape Ann Granite facies. Salem Gabbro-diorite facies is present as a 1.5 mile-wide northeast-trending band north and west of Ipswich.
Retrace route south along Rte. 1A. |
|------|-----|------|
| 14.1 | 0.8 | Jct. with Rte. 133 (Essex Road), turn L (travel east.
Cross extension of large pendant (Stop 4) in vicinity of Candlewood Golf Course. |
| 15.9 | 1.8 | STOP 6. Jct. with Island St.
Quartzose Cape Ann Granite facies, "separated" mafic dikes.
Continue on Rte. 1A. Note view across salt marshes to drumlins and dunes of Castle Neck. |
| 19.0 | 3.1 | LUNCH STOP. Woodmans, South Essex. Sea food, beverages.
Gloucester schooners were built on the tidal inlets here until about 1930.
Continue on Rte. 1A. |
19.1	0.1	Leave Rte. 1A, travel straight ahead on Southern Ave.
19.4	0.3	Re-enter Marblehead North quadrangle.
20.7	1.3	STOP 7. Border phase of large inclusion of Salem Gabbro-diorite facies in quartz-poor Cape Ann Granite facies. Road for next mile follows low ground on strike of a thrust(?) fault.
22.2	1.5	Jct. with Rte. 128, turn east on clover-leaf, following signs for Rockport and Gloucester.
Note pink color of granite in this area caused by hydrothermal alteration.
23.5	1.3	Enter Gloucester 7-1/2-minute quadrangle.
25.0	1.5	STOP 8. Mount Ann Park.
Quartzose Cape Ann Granite facies.
26.6	1.6	STOP 9. Squam Granite facies. Fault trace from Manchester Harbor along Boston and Maine RR route (Lily Pond, Little River, low ground just east of this point, Annisquam River and Loblolly Cove.)

29.7	3.1	Rte. 128 terminus, turn L on Rte. 127 (Eastern Ave.). Travel through Rockport to Pigeon Cove.
30.2	0.5	Enter Rockport quadrangle.
34.2	4.0	Pigeon Cove Forge. Take first right at north end of Forge, then first left. Bear right at all junctions. The "Pigeon Cove Porphyry", a basalt dike containing prominent plagioclase phenocrysts, crops out in the parking lot of the forge, follows the shore southward, cuts through Bearskin Neck, and The Headlands east of Rockport.
35.0	0.8	STOP 10. Andrews Point. Quartzose Cape Ann Granite facies encloses a large xenolith, possibly Squam Granite facies. Reaction has yielded some pegmatites. Annite (Fe-rich biotite) type locality. "Separated" dikes. Retrace route south through Pigeon Cove and Rockport to Rte. 128 terminus. To the west, especially on northern Cape Ann, are many granite quarries, developed in Cape Ann Granite facies rocks having rather uniform textures and containing 15%-25% quartz. The central part of the Cape, known as Dogtown Common, is strewn with large glacial erratics.
39.0	4.0	Re-enter Gloucester quadrangle.
39.5	0.5	Eastern terminus, Rte. 128.

- -

0	0	Optional side trip. Start at Rte. 128 terminus, travel south on East Main St. towards East Gloucester and Eastern Point.
1.6	1.6	STOP 10A. Rhyolite dike cutting quartzose Cape Ann Granite facies; dike shows banding and contains high-quartz forms. Return to Rte. 128 terminus.

- -

39.5 (42.7)	1.6	STOP 11. Eastern terminus of Rte. 128. Inclusions of gabbro porphyry (labradorite phenocrysts) in quartz-poor Cape Ann Granite facies. One of the several "fields" of such inclusions on Cape Ann. Return to Boston via Rte. 128 and Rte. 1. Many exposures of Cape Ann Granite facies.

GRANITE AT MARBLEHEAD--
IGNEOUS OR METAMORPHIC?

S.V. Raman and C.W. Wolfe

Introduction. The best exposure of granite invasion of basic rock in the Greater Boston region is to be seen along the shores of Marblehead, Massachusetts, just north of the boundary line with the town of Swampscott, in the section which is known locally as Clifton. Wave erosion has exposed a remarkably clean section of rock which reveals the extremely varied lithology and structure which occurs at the junction between a pink granite and a highly modified diabase. The area provides a test example of the possible origin of granite in such a geological setting.

Location. The area is immediately accessible to Route 129, just north of the boundary with Swampscott in Marblehead, as indicated by the enclosed sketch map of the area to be described.

General Description of Exposures

The rocks along the 500 feet of shoreline involved in this discussion have only recently been cleared of glacial till by wave action. This fact is indicated by the prevalent glacial striations, polish, and grooving to be seen on the flanks of the southern small peninsula shown on the map. The glacial deposits can be seen resting on preglacial terrace at the 26 foot level. This terrace, plus a forty foot one, is very noticeable along the entire Marblehead coast.

The four major rock types to be seen, from oldest to youngest are: recrystallized basalt, intermediate composition lighter colored rocks, granite, and later basaltic dikes. The recrystallized basalt can be seen as a roof above the intermediate and granitic types, and it is also seen as large inclusions within the intermediate and granite rocks. The intermediate type can be seen as inclusions and as irregular masses with no specific boundaries. The granite occurs as large granitoid masses, as aplite dike-like masses, and as pegmatite veins.

Faulting is omnipresent throughout the area. It is best observed in the offsets of granite dike-like masses as well as in the offset of the late basaltic dikes. The most convincing evidence for faulting in the Greater Boston Region is to be observed where basaltic dikes, one meter wide and 10 centimeters wide which are about 5 meters apart, are offset at least tem times in a distance of 60 meters. A well developed fault line scarp which shows fault breccia and slickensides appears as a 3 meter cliff on the southern edge of the northern peninsula. The large basaltic dike is offset along this fault line. In addition, wave erosion has preferentially carved a channel along this fault line which is much larger at sea level than it is 4 meters higher. When tide level is at the right height, and when waves move into this cave-like opening,

the water converges and occasionally forms a spouting horn with water and
spray rising as much as five meters above the narrow orifice at the inner end
of the cave.

PETROLOGY

The Calfemag Suite. The setting in which the granite formed involved two ma-
jor geological conditions. The first was the development of the Acadian Geo-
syncline with an unknown thickness of sedimentary rocks. The second was the
superimposition of thousands of feet of basaltic flows and tuffs as a cover
to the underlying sediments with their abundant connate sea water. The sedi-
mentary rocks cannot be seen in the area under discussion, but they are
readily observable in schistose form in the Andover, Massachusetts region.

Since the initial texture of the basalts in volcanic piles is vitreous, for
the most part, we are assuming that the vitreous texture was characteristic
of the rocks now exposed in the calfemag suite at Marblehead. None of this
vitreous texture remains in the rocks at Marblehead, although it can be ob-
served in rocks of the same volcanic pile in the Waltham section of Route
128. It is assumed here that the present granitoid texture of the calfemag
rocks is the result of metamorphism and is not the primary texture of the
rocks. Since the texture of marble and quartzite is essentially the same as
that of the calfemag rocks here, and since the textures of marble and quartz-
ite are quite clearly the result of metamorphic recrystallization, this as-
sumption seems fairly safe. We suggest here that the recrystalligation which
changed the basalt glass into basalt and diorite was the result of the same
over-all heating process which ultimately developed the granite or sinak
rocks. This recrystallized rock appears on the southern edge of the third
peninsula without any granite stringers or signs of granite invasion as a
well defined roof over granite which contains extensive inclusions of the
calfemag rock. The typical diabase texture of basalt is largely missing in the
calfemag rocks, but it is present in minor amounts.

Modal Description of Calfemag Rocks. Although flows usually have a monoton-
ous consistency in composition, there is notable variation in the modes of
different specimens of the calfemag rocks. The following table is derived
from point counts of 17 thin sections which have been reduced to averages of
three somewhat different modes.

Modes (volume %) of Calfemag Rocks

Mineral	1	2	3
Quartz	1.54	0.00	0.00
Orthoclase	3.16	3.37	5.26
Orthoclase-perthite	0.00	0.00	0.00
Microcline-perthite	0.00	0.00	0.00
Plagioclase (an 47)	49.50	45.32	45.50
Amphibole	20.00	23.23	26.75
Pyroxene	10.00	4.55	7.75
Biotite	0.00	0.00	9.15
Chlorite	11.60	17.42	2.99
Magnetite	4.20	6.10	2.60
Total	100.00	100.00	100.00

The quantitative variations of the various modes is probably due to variations in metamorphism.

Microprobe chemical analyses were made of perthites, plagioclases, amphiboles, and pyroxenes in the three different rock types at Marblehead. These are not included in this paper but can be examined in the Masters Thesis File in the Boston University departmental offices for geology in Raman's thesis entitled "PETROGENY OF GRANITES AND ASSOCIATED ROCKS AT MARBLEHEAD, MASSACHUSETTS", (1973). On the basis of these analyses and with certain minor assumptions the average chemical compositions of the various rock types can be derived. Such an average chemical composition for the calfemag rocks at Marblehead follows.

Average Bulk Chemical Composition of Basic Rock Types

Mineral	wt%	wt% of various oxides							
		SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	Na_2O	H_2O
Quartz	0.48	0.48	-	-	-	-	-	-	-
Orthoclase	3.00	1.94	0.55	-	-	-	0.51	-	-
Plagioclase	48.30	21.28	21.02	-	-	3.69	-	2.30	
Amphibole	23.40	1.47	4.72	6.45	5.30	4.04	0.57	0.74	0.11
Pyroxene	12.52	8.34	0.32	1.15	0.88	1.78	0.03	0.04	-
Chlorite	12.30	3.48	3.35	2.01	2.71	0.14	-	-	0.60
Totals	100.00	36.99	29.96	9.61	8.89	9.65	1.11	3.08	0.71

Modal Description of Intermediate Rocks. Rocks of the intermediate composition rock suite at Marblehead vary tremendously in texture and mineral composition. Some of the rock is a massive, rather homogeneous syenite. Much of the intermediate compositions are to be seen in the inclusions. The margins of many of the inclusions are surrounded by a hornblend rim which is much darker than the remainder of the inclusions. The inclusions vary from almost unchanged diorites or basalts to nothing but ghost-like areas of slightly differing compositions from the surrounding rocks. Many of the inclusions manifest a pervasion texture of potash spar megacrysts throughout the darker host rock; and there is a complete **gradation** from unaltered inclusions to that stage where the inclusion is no longer visible. Some of the inclusions are sharp and angular; others show gradational margins and are somewhat rounded. We have chosen three differing lithologies for the modal analyses which follow. They are indicative of the variations which can be observed, but they certainly do not embrace all of the possible modes in the intermediate rocks. The compositions of the amphiboles do not change very much from the ferrous hornblendes of the calfemag suite, but the plagioclases change abruptly from An47 to An23, requiring a tremendous introduction of sodium into the system. The grain size of the amphiboles decreases from the calfemag suite to the intermediate suite.

Mineral	1	2	3
Quartz	3.73	11.90	8.10
Orthoclase	5.51	4.00	9.42
Orthoclase-perthite	10.72	8.40	26.00
Microcline-perthite	3.58	2.50	6.00
Plagioclase (an 23)	42.30	37.00	27.70
Amphibole	16.00	9.10	9.30
Pyroxene	7.40	4.10	5.30
Chlorite	7.00	3.37	4.90
Magnetite	2.72	0.11	1.28
Total	100.00	100.00	100.00

The marked increase in potash spar, the decrease in an content, the disappearance of magnetite, and the decrease in amphibole, pyroxene, and chlorite are particularly impressive as appears in the resulting chemical changes indicated by the average bulk chemical composition of the intermediate rocks.

Average Bulk Chemical Composition of Intermediate Rock Types

Mineral	wt%	Wt% of various oxides							
		SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	Na_2O	H_2O
Quartz	6.57	6.57	–	–	–	–	–	–	–
Perthite	41.80	15.90	13.60	–	–	0.96	10.5	0.47	–
Plagioclase	27.82	12.18	10.30	–	–	1.18	–	4.33	–
Amphibole	11.45	0.68	2.05	2.85	3.48	1.79	0.25	0.30	0.05
Pyroxene	6.90	2.70	0.02	0.97	1.52	1.39	0.01	0.08	–
Chlorite	5.46	1.49	1.43	1.29	1.12	0.08	–	–	0.02
Totals	100.00	39.44	27.40	5.11	6.12	5.40	10.76	5.18	0.07

Modal Description of Sinak Rocks. The sinak rocks which were ultimately developed at Marblehead were true granites which were usually pink in color. Orthoclase perthites and microcline perthites were far more abundant than orthoclase. The amount of plagioclase is reduced to roughly one half or less of its abundance in the calfemag and intermediate type rocks. The femag minerals are reduced to about one eighth their abundance in the calfemag rocks. The three modal analyses which follow are derived from ten thin sections which were as judiciously chosen for the sake of variety as was possible.

Mineral	1	2	3
Quartz	21.2	18.10	17.40
Orthoclase	5.56	10.30	8.04
Orthoclase-perthite	27.00	20.23	20.60
Microcline-perthite	18.00	26.50	23.71
Plagioclase (an 21)	24.00	16.50	18.22
Amphibole	5.21	7.35	3.16
Pyroxene	0.13	0.00	0.00
Biotite	0.00	0.00	0.00
Chlorite	0.00	0.00	6.05
Magnetite	0.00	0.00	2.82
Total	100.00	100.00	100.00

The overall decrease in calcium, iron, and magnesium is particularly impressive when the average composition of the sinak rocks is considered. The concomitant increase in silicon and potassium is equally noteworthy, and both facts will be of considerable importance when we discuss the implications for magmatic versus metamorphic origin of the granite.

Average Bulk Chemical Composition of Sinak Rock Types

Mineral	wt%	wt% of various oxides							
		SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	Na_2O	H_2O
Quartz	17.80	17.80	–	–	–	–	–	–	–
Perthite	53.42	23.28	15.77	–	–	1.14	12.69	0.54	–
Plagioclase	16.43	7.80	5.70	–	–	0.55	–	2.34	–
Amphibole	9.35	1.63	2.85	2.30	1.16	1.26	0.02	0.09	0.04
Chlorite	3.00	1.00	1.03	0.88	0.07	–	–	–	0.02
Totals	100.00	51.51	25.35	3.18	1.23	2.95	12.71	2.97	0.06

Summary of Chemical Changes. The chemical changes in the environment are really monumental. Let us assume that the specific gravity of the calfemag rocks is 2.9; that of the intermediate rocks is 2.8; that of the sinak rocks is 2.65. One cubic meter of the calfemag rocks would then weigh 2,900 kg; one cubic meter of intermediate rocks would weigh 2,800 kg; and one cubic meter of sinak rock would weigh 2,650 kg. The following table shows the composition in one cubic meter of the various oxides, exclusive of water.

Oxide Weights in $1m^3$ of Various Rock Types

Oxide	m^3 calfemag 2,900 kg Wt. in kg	m^3 intermediate 2,800 kg Wt. in kg	m^3 sinak 2,650 kg Wt. in kg	Net change in kg
SiO_2	1,073	1,104	1,365	+672
Al_2O_3	869	767	672	-197
FeO	279	143	84	-195
MgO	258	171	33	-225
CaO	280	151	78	-202
K_2O	32	301	337	+305
Na_2O	69	145	79	- 10

The only anomalously behaving oxide is soda. Its decrease in the final stage rocks, the granites, is to be explained in terms of the unstable position of plagioclase in the developing environment.

Probably the most important problem regarding the emplacement of the granite is the destination of the subtracted materials. Since the emplacement of the granite was not accompanied by any marked volume changes, as evidenced by the unfractured roof of calfemag rock above the granite, the calfemag materials which were in the country rock must have migrated somewhere, whether the granite is igneous or metasomatic in origin. If the calfemag constituents had moved outward from the granite body, the roof should be greatly enriched in those elements. There is no evidence for this enrichment. The only conclusion which one can draw is that the calfemag constituents were moving down as the sinak constituents moved upward. It is easy enough to bring sinak components into the region in watery solution; but the mechanism whereby the calfemag constituents move down toward the heat source is less obvious. The calfemag constituents are less soluble in the environment which was developing, as evidenced by the amphibole halo around the inclusions, but how the amphibole constituents completely disappear is a major problem. In all probability, the ions migrate until they are precipitated as less soluble constituents or minerals deeper in the column and nearer the heat source.

Origin of the Rocks at Marblehead

If the granite problem cannot be solved at Marblehead, it is probable that there is little chance of any solution being found. The usual view of these rocks, as suggested by LaForge, is that granite magma in a large batholithic chamber was invading an already emplaced batholithic mass of the Salem gabbro-diorite. The inclusions are xenoliths in the Daly sense of piece meal stoping. The tongues and veins of granitic composition are apophyses. Yet, there seems to be cogent evidence at Marblehead that the granite could be of metsomatic origin. Let us, therefore, submit the field evidence which must be explained, regardless of which approach is used.

    1. The emplacement of the granite is apparently a volume for volume process.

    2. No matter what the origin of the granite, calfemag constituents and alumina must be removed from the region.

3. If the calfemag inclusions are to be digested, a tremendous amount of super heat is required to carry on the process, if the granite came in as a magma.

4. The amphibole rims around the inclusions must be explained.

5. Sinak eyes or sunbursts in the calfemag rocks some distance away from obvious sinak rock need explanation.

6. All degrees of pervasion textures and potash feldspar development in inclusions can be seen.

The explanation for the volume for volume emplacement is easily handled by both approaches to the origin of granite. If the granite came in as magma, the amount the magma rose by piece meal stoping would be equivalent to the volume of material which would settle into the magma and fill the potential void which was produced by the rising of the magma. If the granite were emplaced by metasomatism, the amount of material dissolved from the roof would be exactly equal to the amount of calfemag material which would crystallize in depth. Sinak and calfemag constituents simply exchange positions in equilibrium with the temperature gradient.

Calfemag constituents could be removed readily if the granite were emplaced as a magma simply through the sinking of calfemag crystals in the sinak magma. Certainly, the basic condition of equilibrium for the earth is to have sinak rocks above calfemag rocks. Bowen's Reaction Series suggests that calfemag constitutents dissolve last or crystallize first, and gravitational settling is very possible. The fact that many of the inclusions are in all stages of change into granite just below the calfemag roof, suggests, however, that very little gravitational settling of the inclusions was taking place. Amphibole crystals surround the inclusions; and they probably should have migrated away. We have already indicated that ionic diffusion in a thermal gradient might well produce crystallization of calfemag constituents in depth, with sinak constituents simultaneously moving away from the heat source; but this is problematical at best.

Daly (personal communication) said long ago that his biggest problem with piece meal stoping was the tremendous heat requirement to keep the process going. Of course, if he had visualized an adequate source for the magma generation in the first place, radioactivity, he would not have been so troubled by the superheat requirement. The heat for magma invasion and metasomatism can easily be supplied by radioactivity. In fact, since there can be no other source for the heat, ultimately, there must be enough radioactivity to supply the needed heat.

The pervasion textures and sinak eyes both require sinak diffusion into the inclusions. Since it is possible, as borne out by the existence of these phenomena, the source of the solutions for the diffusion is the major problem. If the solutions are emanations from the granite, the granite should simultaneously be enriched in calfemag minerals. This is not the case. The authors suggest that the sinak solutions are products of solution of sinak sedimentary rocks lying in the geosyncline below the volcanic pile. The volcanic pile acted as a thermal and solution blanket until heating in the

underlying sediments produced an unstable region beneath the pile, and solutions began to move up. Evidences for such permeation of sinak solutions into the overlying volcanics can be seen along Route 128 from Reading to Waltham. It can also be seen along I93 from Woburn to Andover and Tewksbury. Certainly, if solutions from granite magma can permeate inclusions, sinak solutions which are formed in depth in a geosyncline could do the same. The fact that nearly 1,000 kg of sinak substitution and 900 kg of calfemag subtraction has taken place in the Marblehead region for every cubic meter strongly suggests the metasomatic origin. The fact that many granitic dike like bodies apparently required no space for their emplacement also suggests the metasomatic origin. No chill border can be observed between granite and country rock; in fact, the granite masses are usually coarsest near the contacts. This again suggests a metasomatic origin. The basis process, therefore, we believe, is one of differential solution, ionic migration in solution, and crystallization in equilibrium with a thermal gradient downward.

<div align="center">
Outstanding Spots in the Region to be Visited.

Consult the Map.
</div>

Description of Localities at Marblehead-Clifton

1. Best place to start trip. Pervasion textures in calfemag inclusions. Sharp and transitional boundaries. Amphibole rims around some of the inclusions. Pegmatite veins, often zoned. Extensive faulting and re-healing by quartz and epidote. Glacial striae, grooves, and polish. Striae trend S 21 E.

2. More glacial striations. Rock is recrystallized basalt. Faulted pegmatite veins. Sinak eyes in recrystallized basalt.

3. Glacial striae disappearing under till. Faulted 34mm wide aplite "dike".

4. One of many major faults trending N 65 W and vertical. Permeation texture in basalt.

5. Step faulted aplite dike. Pegmatite veins with reaction margins. Sinak eyes. Glaciated old terrace disappearing beneath cover of glacial till. Many deeply weathered pebbles and boulders in the till.

6. Beautiful example of pebble beach with nearly spherical pebbles resulting from the direct inflow and outflow of waves and currents. Northern end of beach is more sheltered and often shows sand instead of pebbles. If the swell is rolling, note the roar of pebbles undergoing autocomminution in the undertow.

7. Ten foot high fault line scarp. Slickensides and breccia can be observed here and there along fault line. Fault zone is geomorphically incompetent. Rock on wall of fault line scarp is largely unaltered "batholith" roof.

8. Pegmatite vein, well zoned with quartz core and vug containing quartz crystals.

9. Basalt dike is beautifully faulted at least four times across peninsula.

10. Spouting horn develops where wave action has produced passage along fault line.

11. Pegmatite pods with quartz cores grading into rocks with pervasion texture.

12. Best exposure of "batholith" roof. Note transition downward.

13. Basaltic dike of locality 9 continues with repeated faulting. 10 cm dike five meters inshore from larger dike parallels the large dike and is affected by the same faults. Here is the best region to study the relationships between inclusions and granite. Pervasion textures in all degrees of development can be seen. Amphibole rims on inclusions. Sharp and imperceptible contacts are both visible. Ghost inclusions are common. Sinak eyes occur in dark rock and in inclusions of dark rock. Small cliff here permits the study of the "batholith" in three dimensions.

Atlantic

0   10   20   30   40 paces
    50   100 150 200 feet
        Scale
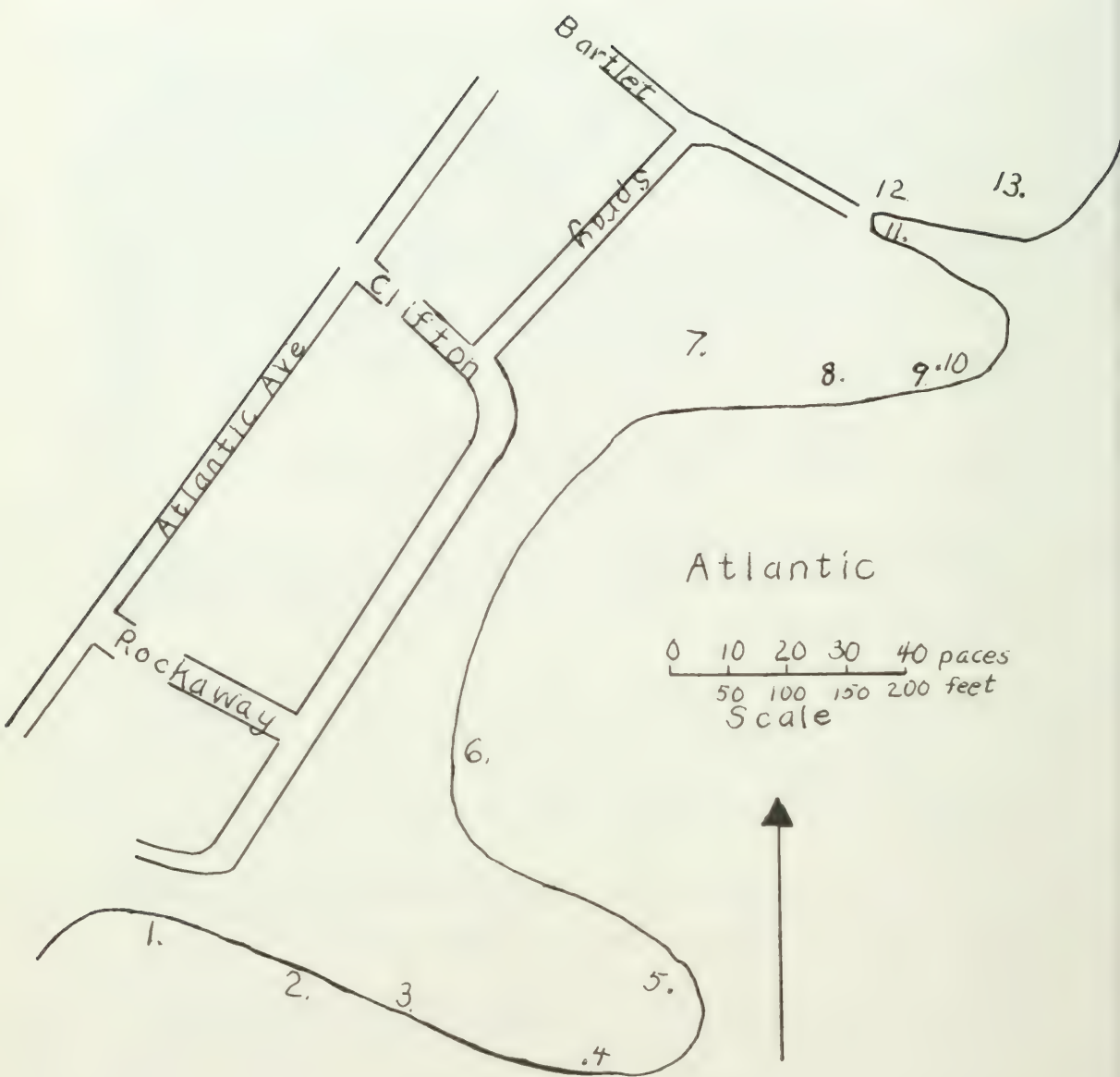
MARBLE HEAD

Trip A-17

PRE-SILURIAN STRATIFIED ROCKS SOUTHEAST OF

THE BLOODY BLUFF FAULT

by Kenneth G. Bell

Road log

This road log begins at the intersection of Hwy 1. (Newburyport Turnpike) and Main Street, Saugus, Massachusetts.

Miles

0-0.8   Exit from Hwy 1 onto the northwest bound lane of Main Street. Proceed 0.8 mile to Stop 1 at parking area on left side of Main Street.

Stop 1: Walk from parking area about 0.3 mile southwest to hilltop. Large exposures of bedrock consist of Dedham Granodiorite enclosing many xenolith and pendants of fine- to medium-grained, thinly layered biotite-quartz-feldspar gneiss. This gneiss is the oldest stratified rock southeast of the Bloody Bluff Fault.

0.8-1.0   Proceed northwest on Main Street, passing the traffic signals at the intersection with Lynn Fellsway, 0.2 mile to road cut on the right side of Main Street.

Stop 2: The cut is in massive quartzite of the lower member of the Westboro Formation. A reddish-brown layer several feet thick is a distinctive marker unit within this member.

1.0-2.2   Proceed northwest 1.2 miles on Main Street to a turn-off and parking area on the left side of street. The parking area is about 100-150 feet south of the power line that crosses over the street.

Stop 3: Walk from the parking area about one mile southwest along the power line and crossing over a hilltop. Beginning at the southwest, there is Dedham Granodiorite intruding the upper member of the Westboro Formation, then a few hundred feet of the uppermost part of the upper member of the Westboro Formation. The contact of the upper member of the Westboro Formation with the overlying Middlesex Fells Volcanic Complex is exposed near the top of the south slope of the hill. Near the top of the hill the volcanic rock is intruded by diorite. On the top and north slope of the hill the diorite and the Middlesex Volcanic complex are over-lain by the Lynn Volcanic Complex.

2.2-8.8   Continue northwest on Main Street 1.1 miles to the junction with Water Street, Wakefield. Turn left onto Water Street and proceed west 1.0 mile to Wakefield Center. Turn left at traffic signal and proceed south 2.8 miles on Main Street of Wakefield and Melrose to Franklin Street, Melrose. Turn right onto Franklin Street and proceed 1.7 miles to entrance of grounds of Stoneham Junior High and High Schools. Enter school grounds.

Stop 4: Rocks of the Middlesex Fells Volcanic Complex are exposed in large cuts along the periphery of the school grounds.

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8.8-17.1   Continue west on Franklin Street 0.7 mile to Stoneham Center. Turn
right at traffic signal onto Main Street and proceed north 1.8 miles to
junction with Hwy 128. Exit onto the southbound lanes of Hwy 128. Proceed
south on Hwy 128 about 5.0 miles to the northbound exit to Route 3A.
Proceed north on route 3A 0.8 mile to entrance to grounds of a factory.

Stop 5: Rocks exposed in the cut leading to the factory parking lot
and at the south side of the parking lot are intrusive rocks of the
Cape Ann Plutonic Series that enclose xenoliths and pendants of amphi-
bolite of the Greenleaf Mountain Formation.

17.1-17.9   Continue north on route 3A 0.3 mile to a traffic light. Turn left at
traffic light into school grounds. Follow road 0.5 mile, bearing left to
south side of High School building.

Stop 6: Quartzite, amphibolite, and gneiss of the Burlington Formation
are exposed in cut at east side of building.

<center>End of trip</center>

STRATIGRAPHY AND STRUCTURAL SETTING

OF THE NEWBURY VOLCANIC COMPLEX, NORTHEASTERN MASSACHUSETTS

by

Andrew F. Shride
U.S. Geological Survey
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The Newbury Volcanic Complex of Silurian-Devonian age (Emerson, 1917, p. 161-164) is exposed mainly in a northeast-trending, wedge-shaped belt (hereafter, for brevity, termed "wedge") in northeastern Essex County. The wedge of Newbury rocks, 16 km long and about 3 km wide in easternmost exposures near the coast between Newbury and Rowley, arcs southward and pinches out in Topsfield (fig. 1). Six kilometres farther southwest, in the northwest corner of the Salem quadrangle, a few small outcrops and rubbly exposures of comparable lithology have been confirmed by fossils as part of the Newbury (Toulmin, 1964, pl. 1, p. A14-17). The wedge is defined on all sides by faults of large displacement; in addition, the wedge is made up of two segments separated by a northeast-trending fault (fig. 1). In the northern segment strata strike northeast and dip mostly northwest at moderate to steep attitudes. In this segment, in which strata are further dislocated by lesser crossfaults, exposures are adequate for straightforward reconstruction of the stratigraphic sequence. In the southern segment exposures are few, and the makeup and interrelations of members in that part can be only roughly defined. Generally, strata of the southern segment strike northerly and dip steeply. Strata along the west border of the southern segment are comparable to those of the south part of the northern segment, thus permitting correlation between the two segments.

Early workers (Clapp, 1921, p. 31) regarded strata of the wedge as disposed in a syncline or otherwise broadly folded and miscorrelated isolated outcrops as though the strata were duplicated in folds. Dos Santos (1960) seems to have been the first to record that the strata are homoclinally disposed; he also enumerated the stratigraphic succession cited in later regional correlations (Boucot, 1968; Gates, 1969). Herein, contrary to published descriptions now available, the succession is considered overturned to face southeast or east; moreover, certain exposures cited inconsistently in previous reports as parts of various stratigraphic elements are recognized here as rhyolitic intrusions, and sedimentary strata previously not described are here recognized. Table 1 provides a brief summary of the stratigraphic sequence as pieced together during recent detailed mapping. More details are given in another paper (Shride, 1976).
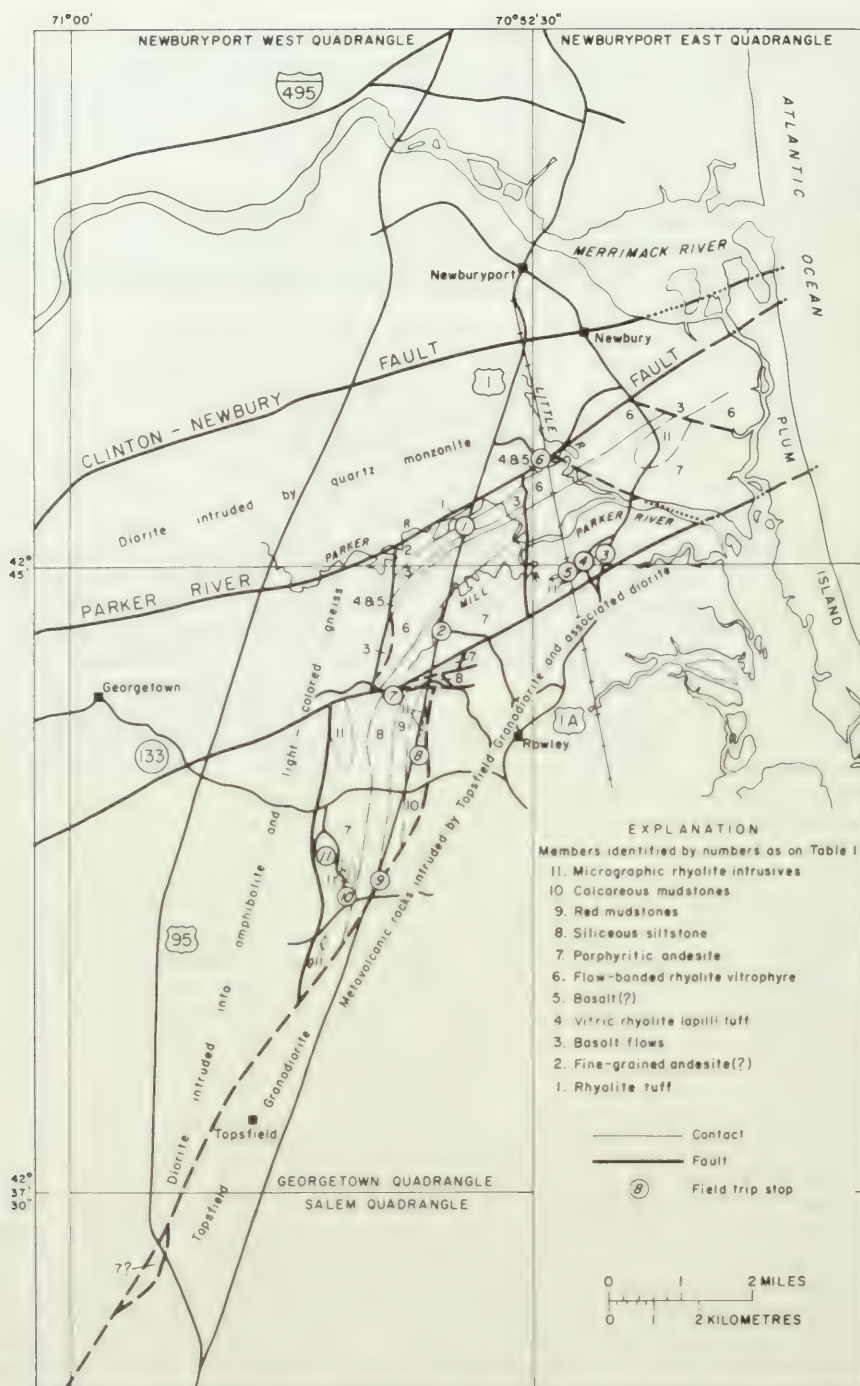
Figure 1.--Geologic map of the Newbury Volcanic Complex

Within the figure:

71°00'   NEWBURYPORT WEST QUADRANGLE   70°52'30"   NEWBURYPORT EAST QUADRANGLE

ATLANTIC

495

OCEAN

MERRIMACK RIVER

Newburyport

Newbury

CLINTON – NEWBURY   FAULT   FAULT

LITTLE

Diorite   intruded   by   quartz   monzonite

PLUM

42°
45'   PARKER   RIVER

PARKER RIVER

WILL

gneiss

ISLAND

Georgetown

133

light – colored   and   amphibolite

Rowley

95

Metavolcanic rocks intruded by Topsfield Granodiorite and associated diorite

EXPLANATION

Members identified by numbers as on Table I

11. Micrographic rhyolite intrusives
10. Calcareous mudstones
9. Red mudstones
8. Siliceous siltstone
7. Porphyritic andesite
6. Flow-banded rhyolite vitrophyre
5. Basalt(?)
4. Vitric rhyolite lapilli tuff
3. Basalt flows
2. Fine-grained andesite(?)
1. Rhyolite tuff

—————— Contact
————— Fault
(8) Field trip stop

Topsfield   Granodiorite

Diorite   intruded   into

Topsfield

42°
37'
30"   GEORGETOWN QUADRANGLE

SALEM QUADRANGLE

??

0   1   2 MILES
0   1   2 KILOMETRES

292

As redefined, stratigraphic units of the Newbury are in different order than the sequence cited for regional correlation by Boucot or Gates. During this field trip, some of the outcrops that are critical to this redefinition will be viewed and features suggesting a variety of environments of accumulation can be interpreted. Further, the significance of the Newbury Complex in the dating of adjacent terranes and in defining some major tectonic events will be considered.

The road log is designed, insofar as practical, to view the members of the Newbury in sequence from bottom to top. Depending on the weather, the level of tidal waters in the salt marshes, and the interests of the participants, the sequence of stops for the NEIGC trip may be retailored in order to provide views of the best outcrops available or a better grasp of details of certain of the several kinds of deposits that can be seen. Asides as to supplementary localities for viewing are provided in the log; these localities are referenced to landmarks identified on the current 7 1/2' topographic maps of the Georgetown, Ipswich, Newburyport East, and Newburyport West quadrangles, enabling the reader to find his own way to additional sites. The independent user of the log, visiting only Stops 1, 2, 3, 8, 9, and 5 or 10 can probably accomplish minimal review of the stratigraphy and lithologies of the Newbury in about one-half day. PLEASE OBTAIN PERMISSION TO TRESPASS.

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TABLE 1. STRATIGRAPHIC SEQUENCE IN NEWBURY VOLCANIC COMPLEX

----Top defined by faults----

11. MICROGRAPHIC RHYOLITE INTRUSIONS--Podlike bodies of brownish-gray to orange-pink, aphanitic to sugary-textured massive felsite. Characterized by micrographic and spherulitic intergrowths; spherulites visible in some outcrops. 100-600 m in thickness and as much as 1,600 m in length

10. CALCAREOUS MUDSTONE MEMBER--Laminated gray limestone and mudstone, very thinly interbedded. Large ostracodes characteristic. At least 90 m; possibly 300+ m in thickness

9. RED MUDSTONE MEMBER--Grayish-red, friable, micaceous sandy mudstone. Boundaries indeterminate; with (8) and (10) totals 1,500 m in thickness

8. SILICEOUS SILTSTONE MEMBER--Dusky yellow green to olive-black, dense, flinty rock; parallel stratification inconspicuous

7. PORPHYRITIC ANDESITE MEMBER--Propylitized grayish-green to dark gray andesite, typified by plagioclase phenocrysts. Nonstratified volcani-clastic layers, ranging from fine-grained tuffs to boulder breccias, are much more voluminous than intercalated flows; stratified graywacke is subordinate. Sparsely fossiliferous. 1,650+ m thick

----Local(?) erosion----

6. FLOW-BANDED RHYOLITE VITROPHYRE MEMBER--Dense, lithoidal vitrophyre, mostly grayish red and conspicuously laminated; large parts not por-phyritic; includes sparse lenses of vitric tuff; locally basal 120 m is pumiceous tuff. 580-670 m thick

5. BASALT(?) MEMBER--Dense, tough, dark gray, structureless rock. 0-90 m thick

4. VITRIC RHYOLITE LAPILLI TUFF MEMBER--Grayish-green, friable, hackly fracturing tuff, in which flattened pumice fragments are abundant in shard-rich matrix. 0-52 m thick

3. BASALT FLOW MEMBER--Uniformly fine-grained propylitized flows, devoid of fragmented materials; each 30 m or more thick, and separated by thin lithified soil(?) zones. 250-300 m thick

2. FINE-GRAINED ANDESITE(?) MEMBER--Thoroughly propylitized, very fine grained, olive to olive-brown rock; part conspicuously to vaguely lami-nated, part massive and amygdaloidal(?). 275-m interval between members 1 and 2, with only 80 m of strata exposed

1. RHYOLITE TUFF MEMBER--Flinty yellow-brown to brownish-gray vitroclastic rock, studded with darker fragments that are felted in texture. 6 m thickness

----Bottom defined by fault----

Aggregate thickness
probably more than 4,400 m

Road Log

Assemble at the junction (designated Kent Corner on Georgetown Quad) of U.S. Highway 1 (Newburyport Turnpike) and State 133 by 7 A.M.

Mileage

0.0   Proceed north on U.S. 1 from junction with State 133.

3.8   STOP 1. At south bank of the Parker River, park as far off high-
       way as possible. POISON IVY AND POISON SUMAC everywhere, this
       stop. Tide permitting, exposures of the lowest two members of the
       Newbury will be viewed in the salt marshes to the N. The rhyolite
       tuff outcrop (member 1, Table 1), 1,000 feet NW of the Parker
       River bridge, is well preserved considering that it borders the
       Parker River fault zone. Along the SE margin and on top of the
       island 500 feet NW of the bridge, note the variety of textures and
       structures in the fine-grained andesites (member 2, Table 1).

       From the parking site, members 3, 4, 5, and 6 (Table 1) can be
       crossed in succession by walking 1,500 feet NE along the south
       bank of the marsh and then wending a route southward across the
       more prominent outcrops that will come into view. In the basalt
       flows (member 3) note the uniform fine texture, lack of detrital
       materials, and difficulty of recognizing flow boundaries--which
       are usually in the swales. Outcrops of members 4 and 5 are few
       and border the marshy meadow S of the basalt ridge. Flow-banding,
       which becomes wider spaced upward, and intricate slump structures
       are readily seen in the rhyolite vitrophyre (member 6); zones of
       spherulites and lithic tuffs may be crossed. After reaching the
       bluffs that overlook the marshes of the Mill River, a traverse
       along the S margins of the islands that extend E to the junction
       of the Parker and Mill Rivers provides good views of the flows
       that dominate the basal 600 feet of the porphyritic andesite member
       (member 7). Volcaniclastic strata will be dominant higher in the
       member. On the W end of the island, 500 feet SW of the river junc-
       tion, two conglomerate beds contain water-worn rhyolite pebbles
       derived from member 6, providing one item of the evidence for an
       overturned section. This conglomerate can be traced NE to Little
       River.

       On return to the highway, PLEASE DO NOT INTERFERE with play on the
       Old Newbury golf course.

       From parking site, turn around, WITH CAUTION, and proceed S on
       U.S. 1.

3.9 Low roadcuts on both sides of road (1,500 ft S of Parker River bridge) are of the rhyolitic lapilli tuff (member 4, Table 1), in which many pumice fragments are tabular, as though flattened, but shards of the matrix are only slightly compacted.

4.1 Outcrop at entrance of Old Newbury Golf Club is the dense basalt(?) that intervenes between the rhyolite lapilli tuff and banded rhyolite vitrophyre members. Brown streaking is atypical.

4.1+ High roadcut (2,300 ft S of Parker River bridge) exposes transition zone at the top of the tuff that here locally constitutes the basal 400 feet of the flow-banded rhyolite vitrophyre (member 6).

4.3 Elm St. on right. Bluff 0.2 mile SW, at the junction of roads on the Governor Dummer Academy grounds, provides an alternate exposure for viewing member 6.

4.9 Bridge across Mill River. At low tides, epiclastic strata, common in the porphyritic andesite member but very friable and not seen in proportion to their occurrence, are visible in the streambed above and below the bridge.

5.3 Turn left (E) onto Central St. and stop off road as soon as feasible; leave room for trailing cars.

STOP 2. Intercalated flows and water-laid ash-fall(?) tuffs of the porphyritic andesite (member 7). The first reported fossils ("marine types" comprising "one or more species of brachiopods, a species of gastropod, fragments of crinoids, and probably a pelecypod"--see Emerson, 1917, p. 163) from the Newbury were collected here, apparently at the road intersection in rocks now deeply buried. Similar thin fossil zones exist in the vicinity, and additional collections were made in the 1960's; the sites may not be accessible now. Note zones of alteration and the differences between flows and tuffs.

Continue E on Central St.

5.9 The fault that occupies this topographic saddle separates the north and south segments of the Newbury wedge farther west. The outcrops just ahead, and all those along the route to mile 9.4, are of Topsfield Granodiorite, described by Toulmin (1964) at a locality 7-10 miles to the SW. The pluton, identified as different formations, has been described as being intrusive into or, alternately, as being unconformably overlain by the Newbury--rather than in fault contact. The pros and cons of the three interpretations will be considered.

6.3 The road to the left (E), if followed NW along the southwest foot of Ox Pasture Hill (Georgetown Quad) to its end, gives access to good exposures of flows and coarse volcaniclastic layers in the porphyritic andesite member.

6.9 Turn left (E) onto Cross St.

7.6   Turn left (N) onto Highway 1A.

9.4   At the south edge of the marshes, again cross the boundary fault,
        and again traverse the porphyritic andesite member.

9.8   STOP 3. Sedimentary rocks of the porphyritic andesite member.
        Park well off road, AVOIDING BOULDERS. The main exposure on the
        west side of the road may not be in place, but it does show bed-
        ding structures indicative of bedding-top directions and of the
        kind that can be seen in less accessible localities. Flow tops
        and coarse clastic rocks can be seen on east side of road.

        Continue N.

9.9   Turn sharp left at next intersection. Porphyritic andesite flows
        that crop out along the next 0.5 mile are petrographically similar
        to those near the base of the member (Stop 1), but are thinner and
        intercalated with much water-laid andesitic material. Here the
        flows are about 3,500 feet above the bottom of the member.

10.6   STOP 4. Laharic(?) deposits of member 7. Park so passage is
        possible along this narrow lane; walk 100 ft W along path. Out-
        crops at this locality are ephemeral! If outcrops are visible,
        note the variety of clasts, differences in their weathering "rinds,"
        and bedding structures or lack thereof. Outcrops of fine-grained
        graywackes at water's edge, 500 ft NW and across the marsh, display
        both cross-lamination and graded bedding, which indicate an over-
        turned section with tops facing SE.

10.7   Turn right (SW) at town line marker and follow "track" past dump
        area.

10.9   STOP 5. Micrographic rhyolite intrusion. Cross railroad, turn
        right (N), and PARK WELL CLEAR OF PASSING TRAINS. The rock in the
        cut just to S is smoke smudged and somewhat etched by train fumes,
        but otherwise is representative of the intrusive rhyolite that
        occurs as podlike bodies disposed subparallel to stratification at
        various horizons in the Newbury. In some of the rock, minute
        spherulites can be discerned with a lens. Under the microscope,
        these spherulites are micrographic, as is part of the matrix.

        Continue N along railroad--SLOWLY--WATCH FOR AXLE-BREAKING HOLES.

11.9   The rhyolite-pebble conglomerate noted at the junction of the Mill
        and Parker Rivers occurs in low outcrops in the marshes SW and NE
        from here, but is between compacted andesite tuffs rather than
        flows.

12.0   These railroad cuts through Kents Island are smudged outcrops, un-
to   satisfactory for viewing, of the flow-banded rhyolite vitrophyre
12.2   (member 6). Outcrops farther east can be viewed easily, and some
        include lenses of crystal-lithic rhyolite tuff. The round hill to
        the west (accessible by road from mile 12.8) is a rock drumlin with

glacial pavement at grass-root depths. If the turf is breached at certain localities on the north slope, one might be able to view spherulites as much as 2 cm in diameter (the "frog-eyes" of local jargon). These occur sporadically along one or two zones, about at midsection, throughout the outcrop length of the vitrophyre member.

12.6   Turn left (W) onto Hay St. and park 0.1 mile W along roadcut in granitic rock.

STOP 6. Parker River fault. This breccia of quartz monzonite marks the north border of the fault zone that truncates the Newbury and everywhere defines its north boundary.

Continue NW on Hay St.

12.8   Road on left (S) provides access to Kents Island, home of the late novelist, J. P. Marquand.

13.2   At junction, continue left (W) onto Boston St.

13.6   Turn left (S) after stop onto U.S. 1.

17.1   Turn right (W) at Dodge Corner (see Georgetown Quad) onto Wethersfield St., which here roughly follows the fault that separates the north and south segments of the Newbury wedge.

17.5   STOP 7. Siliceous siltstone (member 8). Follow path S 200 ft to small purplish-black outcrop. Exposures of this member are very few. Most are much lighter colored--commonly yellowish green--than this outcrop.

Drive W 0.15 mile to road intersection; turn about and return to U.S. 1.

18.2   Turn right (S) onto U.S. 1.

19.3   STOP 8. Calcareous mudstone (member 10). Pull well off highway onto right shoulder. Walk across highway onto ungraded road. Exposures are on this road and in the field to N. The large ostracodes (leperditiids) that are a characteristic of this member are seen most readily on parting surfaces of slabs that have been recently uprooted and weathered a few months to facilitate splitting.

Continue S on U.S. 1.

21.1   STOP 9. Red mudstone (member 9). Turn left across highway and park in open area (800 ft N of intersection of Linebrook Rd. and U.S. 1). The quarry face to the E is the only known outcrop of the member. Elsewhere, the red micaceous mudstone seen here occurs as concentrations of shaly or flaggy detritus in the soil or of friable erratics distributed to suggest that the member may be several

hundred feet thick. Chips of the yellowish-brown, medium- to coarse-grained sandstone, found here as lenses, can be seen in soils elsewhere; but the andesitic(?) pebbles, cobbles, and flow rock seen toward the north end of this outcrop have not been recognized elsewhere.

END OF TRIP

For those interested in additional aspects of the Newbury, the following short traverse is appended. This can be started at the next intersection to the S or be followed in reverse from the assembly point at Kent Corner.

Mileage

0.0   Turn west off U.S. 1 onto Linebrook Rd.

0.4   Junction Linebrook Rd. and Leslie Rd., turn right (N).

       STOP 10. The rim of the bluff just to NE of this intersection ex-
       poses outcrops more typical of the micrographic rhyolite intrusions
       than the outcrop seen at Stop 5.

       Continue N on Leslie Rd.

0.9   At junction, turn left (NW) onto Ellsworth Rd. In this area the
       upper part of the porphyritic andesite member is exposed. In
       general, this part includes fewer flows and more mudstones and
       sandstones than lower parts of the member.

1.0   Ledge to right (N) is Pulpit Rock.

1.2   STOP 11. Much variety of andesitic rock types can be seen from
       this locality: crystal-lithic tuffs and comparable flow rock to
       the E at Pulpit Rock (0.2 mile to the N, coarse breccias of similar
       rock make up the clasts in boulder conglomerate); highly amygdaloi-
       dal but coarsely porphyritic rubble--once probably a glassy flow--
       is exposed behind the ruined buildings to the north; and fine-
       grained flows interlayered with andesitic mudstones occur on the
       wooded nose 500 ft to the NW. Certain of these rusty-weathering
       mudstones have yielded abundant macrofossils.

       Continue W and N along Ellsworth Rd.

1.7   Junction with Leslie Rd. Continue N.

1.8   Road junction, stay right. Cuts made during home construction
       ahead on left have provided good exposures of coarse andesite
       breccias.

2.0   Junction with Haverhill St. (State 133); turn right (E). Glacially
       smoothed knob just E of junction shows in detail the contacts

between layers of various breccias, tuffs, and flows of the porphyritic andesite member; and, before the houses were built, flow borders indicative of east-facing strata tops could be seen.

2.5 At times, depending on the state of quarrying in the gravel pits
to   to the N along this interval, large erratics of andesite that in-
2.9 clude seams of fossiliferous mudstone are left behind. These
     rather friable erratics probably are not far from source. The
     contained fossils are comparable to those collected near Stop 11
     and commonly better preserved. Several collections made from these
     pits by N. P. Cuppels (1967) proved very useful supplements to the
     collections found in place. Furthermore, Cuppels discovered all
     of the sites away from the original Glen Mills site that are noted
     in this log, and made collections that have confirmed and somewhat
     more narrowly defined the Silurian-Devonian age of the Newbury.

3.2 Junction with U.S. 1--assembly point.

   Those who wish to exit north can traverse State 133 west to U.S. 95 or
can follow U.S. 1 north. U.S. 1 is the best route south.

FAULTS AND RELATED DEFORMATION IN THE CLINTON-NEWBURY--

BLOODY BLUFF FAULT COMPLEX OF EASTERN MASSACHUSETTS

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Eastern Massachusetts is a highly faulted region (Skehan, 1969, and Barosh, Pease, Schnabel, Bell and Peper, 1974) in which a great deal of mapping has been done to document the structure. The faults are recognized by dislocations of geologic contacts, omissions and repetitions of stratigraphic units, and abrupt changes in metamorphic grade; an unusually large number of faults, which form parts of the major fault zones, are directly observable in natural outcrops, expressway cuts, and tunnels in the region. The faults show a wide variety of types of deformation and degrees of complexity of structures and history. Fault-related features in the region include: shears, mylonite, gouge, breccia, mineralization and alteration effects, silicified zones, and drag folds. Both compressive movements have been recorded. In addition, fault-controlled emplacement of both large and small intrusive bodies can be demonstrated.

The area between the Clinton-Newbury and Bloody Bluff fault zones (fig. 1) forms a northeast-trending, northwest-dipping thrust-fault complex with west over east and right-lateral components of movement (Skehan, 1969, Alvord, Bell, Pease and Barosh, in press). The deformation related to the main faults in this complex and in the subparallel Wekepeke fault zone to the northwest can be directly observed at many places.

Figure 1. Major faults related to the Clinton-Newbury--Bloody Bluff fault complex of eastern Massachusetts. Numbers denote stops in the road log. Fine lines and route numbers denote major highways. F.Z., fault zone. Modified from Barosh, 1974, Alvord, Bell, Pease, and Barosh, in press, Nelson, 1975b, Peck, 1975, and unpublished data by P.J. Barosh, K.G. Bell and J.H. Peck.
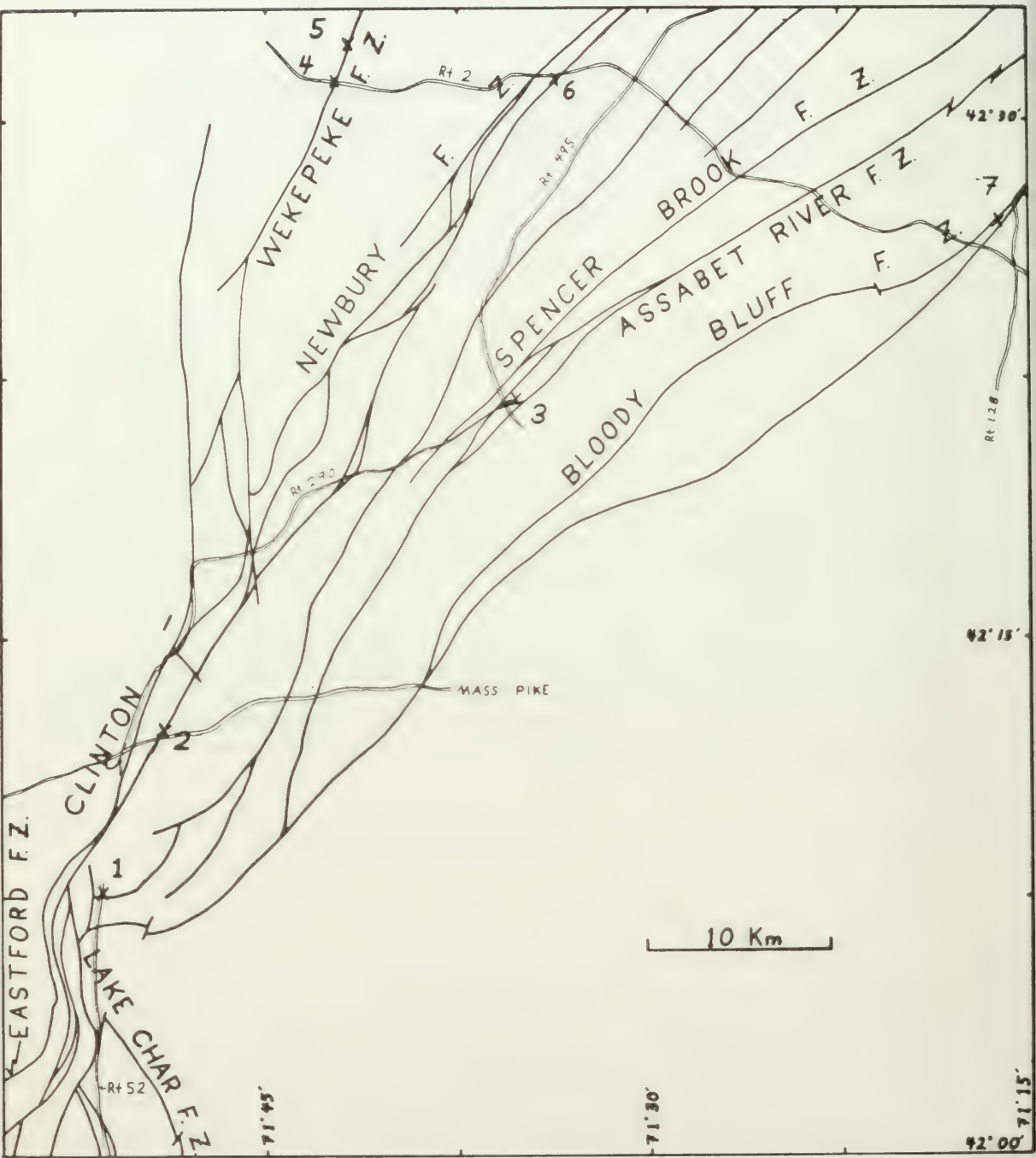
DESCRIPTION

7 1/2-minute topographic quadrangles covering this guide are: Ayer
(Stop 6), Clinton, Concord (Stop 7), Grafton, Hudson, Leicester, Marlborough
(Stop 3), Maynard, Oxford (Stop 1), Shirley (Stops 4 and 5), Shrewsbury,
Worcester North and Worcester South. (Stop 2) Geologic maps for the Framing-
ham and Natick quadrangles, crossed on the Massachusetts Turnpike are available
(Nelson 1975a,b).

ROAD LOG

Mileage

0	Proceed west from Boston University and enter interchange 18 of the Massachusetts Turnpike, Rte. 90, westbound. Mileage begins at the junction of the entrance ramp with the westbound lanes of the Massachusetts Turnpike. Mileage is given for junctions from interchanges farther west so the guide can be started elsewhere along the Massachusetts Turnpike. This part of the route crosses the sedimentary and volcanic rocks of the Boston Basin.
7.5	Charles River. Position of the north-northeast-trending Boston Basin fault bounding the west side of the basin. Precambrian Dedham Granodiorite to the west.
7.8	Crossing under Rte. 128.
8.0	Entrance ramp from Rte. 128.
8.7-9.6	Outcrops of Dedham Granodiorite and gabbro (Nelson 1975b).
11.3	Natick town line. Road is following a fault along here.
11.6	Outcrops of precambrian metasedimentary rocks of the Rice Gneiss (Nelson, 1975 b) on right of road, north of the fault.
11.8 - 12.2	Outcrops of Dedham Granodiorite on left, south of the fault.
13.9	Wayland town line and Lake Cochituate.
14.3	Crossing north-northeast-trending fault, metamorphosed volcanic and volcanoclastic rocks of the Cherry Brook Formation (Precambrian Z to lower Paleozoic?) (Nelson, 1975a) to the west.
14.4	Framingham town line.
14.6	Entrance ramp from interchange 13, Natick.

16.4-17.4	Sudbury River on left; mixture of rocks of the Cherry Brook Formation, Milford Granite and Salem Gabbro-Diorite along here. Farther west is the Milford Granite with scattered pendants and xenoliths of Precambrian Westboro Quartzite.
17.0	Howard Johnson's.
18.0	Outcrops of Milford Granite on both sides of road.
19.1	Reservoir No. 3.
20.3	Entrance ramp from interchange 12, Framingham, Rte. 9 intersection. Milford Granite crops out in the interchange, and Westboro Quartzite crops out at the north edge of the interchange. Scattered outcrops of Milford Granite are along the roadway for about the next 4 miles. The rock is very slightly to well foliated; jointing is parallel to the foliation.
21.4	Southborough town line.
24.9	Hopkinton town line.
25.1	Cross under Rte. 495.
25.6	Entrance ramp from Rte. 495.
27.0	Entrance to Howard Johnson's and start a series of roadcuts in Milford Granite over the next 3 miles. The supposed Milford is well foliated, joints parallel the foliation; the rock here is finer grained than those passed earlier and has a quartzitelike appearance. It may possibly be a different intrusive rock.
27.4	Westboro town line.
29.0	Upton town line.
30.2	Westboro town line.
30.5	Grafton town line.
30.7	Crossing major fault zone; the same zone of pavement as the Bloody Bluff fault zone, if not the same fault itself.
31.0	Low outcrops both sides of road of sheared to mylonitized and partially brecciated granitic and more basic gneiss and some less sheared diorite and vein quartz.
31.5-31.7	Outcrops emerging from a drumlin to the east are of granitic complex that is slightly foliated to highly sheared or mylonitized and cut by many small faults. Road appears to follow one fault strand.

31.8-32.1	Gneiss and amphibolite that is highly sheared, contorted, and locally mylonitized adjacent to several faults that cross the pike about parallel to the overpass bridge here. The chloritic schist here appears to be recrystallized gouge. A few very fine-grained greenish-gray to buff silicic layers are present. These outcrops appear to be part of a large fault zone.
32.8-33.2	Highly contorted amphibolite of the Marlboro Formation forms the east end of the outcrop. It is cut by a light-gray granitic dike at 32.9, which is an apophyse from the granitic intrusive body that forms the outcrop west of 33.0.
33.2	Quinsigamond River valley; a northwest-trending valley several miles long that is probably fault controlled.
34.0	Drumlin cut.
34.6	Outcrops of gneiss of the pre-Silurian Nashoba Formation. Altered and rusty weathering at east edge.
35.8	Entrance ramp from interchange 11, Worcester.
36.8-38.0	Nashoba Formation.
38.4	Blackstone River valley.
39.0	Auburn town line.
39.1-39.6	Nashoba Formation. A strand of the Clinton-Newbury fault zone passes through the valley to the west.
40.5-40.6	Dark-gray phyllites of the Silurian (?) Eliot Formation. The Eliot Formation forms a fault sliver between two strands of the Clinton-Newbury zone; the western strand is at the east edge of the valley, 40.8.
41.0	Drumlin cut. The north half of the drumlin was used to fill in a pond to the northeast, creating a flat area for the Auburn shopping mall. The valley here, which continues north through Worcester, is formed in the faulted soft rocks of the Oakdale Quartzite of Silurian and Devonian age.
41.8	Right into exit 10, Rte. 12-Rte. 290 to Auburn-Worcester. Roadcut in dark-gray metasiltstones of the Oakdale Quartzite.
42.5	Toll booth; stay to right at split for Rte. 12 south to Oxford-Webster. Right on Rte. 12.

43.6	Veer right at signal at Rte. 12 and Rte. 20 junction. Driving over Oakdale Quartzite.
44.3	Left onto Rte. 12 south to Oxford-Webster. Biotite quartz monzonite forms the hill to the left, and the ridge to the right is composed of muscovite quartz monzonite, the Fitchburg Granite.
44.8	Outcrop on right is silicic laminated Oakdale; a short distance ahead, the intrusive bodies on either side merge, pinching out the Oakdale. The Oakdale reappears at the same position about a mile farther southwest.
45.9	Outcrops of quartz monzonite on both sides of valley. Intrusive bodies in this area tend to be long and narrow. Some intruded fault zones are shown by disjunctions between rocks on either side of the intrusive body and by xenoliths of mylonite. Some also have moved along contacts.
46.5	Clinton-Newbury fault zone traverses valley on left and crosses road.
46.9	Boulders on left are a variety of intrusive rocks from the fault zone; many are highly sheared to mylonitized. Outcrop of Nashoba on left just beyond restaurant. Large Pleistocene river in this valley disgorged sediments into a lake here, building a large flat-topped delta to the south, on which the center of Oxford is built.
49.0	Oxford Center. Left onto Sutton Ave.; sign points to Rte. 52, Webster.
49.4	Cross Rte. 52. The hill to the south marks the northwestern corner of the igneous complex of Rhode Island. The hill outlines the nose of a large northwest-plunging anticline cored by granitic gneiss and rimmed by quartzite of the Plainfield Formation. The valley this side of the hill is underlain by amphibolite of the Marlboro Formation in a major fault zone; the same zone of movement was crossed earlier on the Turnpike at mile 30.7. The entire Marlboro is cut out against this fault a couple of miles to the east and less than a mile to the west.
49.7	Road junction on the left. Carefully make a U turn here and return west on Sutton Ave.
49.9	Right at entrance road to Rte. 52 north; no sign at present as Rte. 52 is not officially opened north of Sutton Ave. Marlboro-Nashoba contact exposed at south end of roadcut on the right. Rocks broken by many thrust faults and highly sheared. The contact may be repeated by a small fault.

50.4-50.7	Park by large roadcut on right STOP 1, Thrust-fault complex cutting the Nashoba Formation of Hanson (1956). Complex of moderately north-dipping shears, thrust faults, and overturned folds with north-dipping axial planes. Consistently north over south transport, which is a local deviation from the regional northwest over southeast transport. The foliation parallels relict bedding. Many of the thrust faults have pegmatite, both foliated and nonfoliated, along them. In this area, the Marlboro-Nashoba sequence has undergone radical tectonic thinning by omission along both the boundary faults and a series of internal faults. The thickness changes from 15,000 m to the north near Littleton (Alvord, this volume) to less than 1,000 m south of Oxford Center.
50.9	Turn around across center divider and head south on southbound lane of Rte. 52. End of present Rte.52. Go to next interchange to turn around when the road is finished.
52.0	Right on exit ramp Sutton Ave., west to Oxford, and right on Sutton Ave.
52.6	Oxford Center, right on Rte. 12 to Auburn-Worcester.
54.9	Right at signal on Oxford St. Road follows along northwest side of the Clinton-Newbury fault zone.
56.2	Auburn town line.
56.3	Powerlines. Quartz monzonite crops out on left. Nashoba is across the valley to the right.
56.9	Fault zone splits near here; an east branch continues northeastward, and a west branch goes north through Eddy pond ahead. Fault sliver of Eliot Formation appears between the branches to the north.
58.2	Right on Rte. 20.
58.4	Cross Rte. 290. Outcrops of Oakdale on the left along Rte. 290.
58.6-58.8	Cross fault and pass through roadcut of Eliot Formation.
59.4	Cross a strand of Clinton-Newbury fault zone. Road bends to the northeast and follows Nashoba along the southeast side of the fault zone.
60.8	Pass under Turnpike.
61.0-61.3	Outcrops of Nashoba on right.

61.6	Left into trailer park entrance at Clark Cortez sign. Stay to right at split and drive along dirt road near the stream.
61.9	Park on right. Walk up stream to cut, which is entrance to diversion tunnel, 75 m ahead. STOP 2, Shearing in the Clinton-Newbury fault zone. The eastern end of the cut exposes strongly sheared rusty-weathering muscovite schist of the pre-Middle Ordovician(?) Tadmuck Brook Schist, which overlies the Nashoba. A strongly foliated granitic sill cuts the schist where the side stream enters from the south. A short distance farther west, a strongly foliated quartzose feldspathic gneiss layer is interbedded in the schist. A few north trending faults can be seen here. A granitic dike is at the top of the slight knoll. A well-bedded metasiltstone above it is of Silurian(?) age and conformably underlies the Eliot Formation to the north of Worcester (Peck, 1975). Be very careful here; the edge of the cut is dangerous. Continue down road.
62.1	Left on second street. Return to the entrance.
62.3	Left onto Rte. 20.
62.7	Left on Greenwood St.
63.8	Outcrops of Nashoba in the park on left.
64.5	Left on Butler St. The Clinton-Newbury fault has been crossed, and here we are crossing a fault sliver of Eliot, which is wider than it is to the south. Valley to the right is along a northwest cross fault. Holy Cross College is on the left.
65.4	Holy Cross stadium. West boundary fault near west edge of stadium.
65.5	Pass under Rte. 290 and turn left on Riverside St. Left on next corner towards Rte. 290, and follow road as it curves to right. Take left lane at split at 65.9, curve to left following Rte. 290 east signs and pass under Rte. 290. Continue swinging to left, cross intersection with signals, and enter ramp for 290 east to Marlborough, at 66.4.
67.9	Outcrops of Oakdale.
68.9	Outcrops of granite on Millstone Hill on right.
70.0	Stay to left and continue east on Rte. 290.
70.8	Outcrops of Oakdale.

72.4	Lake Quinsigamond, Fault junction here (fig. 1). Recrossing a branch of the Clinton-Newbury fault zone, where it is apparently cut by a north-northwest-trending fault that passes through this long narrow lake.
72.9-76.3	Scattered outcrops of Nashoba along road. This section of the Nashoba lies between two branches of the Clinton-Newbury and is a partial repetition of the main body of Nashoba farther east.
76.8	Roadcut in intrusive-metasiltstone-phyllite complex. An eastern branch of the Clinton-Newbury fault crosses road in low point just ahead.
77.3	Northboro town line. Rusty-weathering, highly sheared Tadmuck Brook Schist on right and in outcrops within Church St. interchange ahead.
77.8	Nashoba exposures. Outcrops of Nashoba are scattered along the rest of Rte. 290. Some are highly faulted; drag folds are common.
82.9	Rte. 290 - 495 intersection: Present end of Rte. 290. Pull off to left and park near barrier or behind it if possible. STOP 3. Faults related to the Spencer Brook and Assabet River fault zones. Interbedded gneiss and schist of the Nashoba Formation of Hansen (1956), which here is probably equivalent to the Fish Brook Gneiss (Castle, 1965), crops out along with some pegmatite and gabbro. Many small faults offset these rocks. A fault defined by a wide gouge zone and a thin mylonite zone parallels Rte. 290 just south of the road-bed and is exposed on Rte. 495 and on both sides of the entrance ramp from Rte. 290 east to Rte. 495 north. The area here is caught between the convergence of the northeast trending Spencer Brook fault in the valley to the north and the Assabet River fault to the south (fig. 1). A more open brittle type of fracturing is seen here than that at the first two stops. Right onto entrance to Rte. 495 north.
83.2	Enter Rt. 495 north.
83.8	Hudson town line and Assabet River. Cross Spencer Brook fault. Nashoba crops out on hill to north.
85.5-85.7	Rte. 495 - Rte. 62 interchange. Nashoba Formation, Fort Pond Member of Bell and Alvord (in press), well exposed.
86.0	Bolton town line.
88.6	Right on exit for Rte. 117 to Bolton-Stow, right onto Rte. 117 west and pass under Rte. 495. Walls and scattered outcrops of Beaver Brook Member of Nashoba ahead.

89.7	Bolton Center.
90.3	Outcrop of Tadmuck Brook Schist on left.
92.1	Cross Rte. 110, northwest margin of the Clinton-Newbury zone passes through the valley ahead.
92.4	Lancaster town line.
92.9	Cross Nashua River, stay on Rte. 117.
94.3	Right onto Lunenburg Road at North Village. Driving mainly over the Eliot Formation, part of the Worcester Phyllite as used by Emerson (1917).
98.0	Cross over Rte. 2 and turn right into entrance for Rte. 2 west, Gardner - Greenfield.
98.6	Right into exit for services, Howard Johnson's. Park at west end of service area and walk west along north side of Rte. 2 to roadcut. STOP 4, Wekepeke fault zone (Novotny, 1961). Broken, sheared, drag folded, and altered Oakdale Quartzite along the west side of the Wekepeke fault zone, just walked over. Eliot borders the fault on the east. Continue driving west on Rte. 2.
99.3	Right into exit for Harvard St. - Mechanic St. Bend to right, pass under Rte. 2, turn right at next two splits, and enter Rte. 2 east at 99.6.
100.6	Right off Rte. 2, just beyond overpass, for Lunenburg Rd. Fort Pond Rd. Continue to right and pass over Rte. 2 on Lunenburg Rd., north.
102.0	Cross Wekepeke fault. Quarry at left in fractured ankeritic Oakdale.
102.2	Right onto Shirley Road.
102.4	Right into parking lot of Keating Quarry and Park. Walk across road at parking lot entrance, continue into woods 20 m, turn left up old road 50 m to top of gravel bank and turn right at east side of hill crest. STOP 5, silicification along the Wekepeke fault zone (Novotny, 1961). Silicification along fault zones in eastern Massachusetts is unusual, but it becomes more common to the north and occurs in many places in southern New Hampshire. Good examples here are in scattered natural outcrops. Right on Shirley Road.

102.5	Swing right back into parking lot at its east end, go 50 m, and turn left into road along north side of quarry. Quarry is in faulted and contorted Eliot Formation with many drag folds and overturned beds.
102.8	Make a sharp left turn onto Shirley Rd. and return to Rte. 2. After turning left, look to right at the bare slope beyond the quarry buildings. The large white to buff outcrops are manmade exposures of the Wekepeke silicified zone.
104.6	Left into entrance for Rte. 2 east, Boston - Fort Devens.
107.0	Outcrop of Eliot Formation on the left.
108.1	Outcrop of lower part of Eliot Formation on the left.
110.2	Outcrop of quartz monzonite. Traveling along intrusive complex on northwest side of the main Clinton-Newbury fault zone for the next few miles.
110.8	Pass under bridge and turn right at exit to Rte. 110-111 north, Ayer - Groton.
111.4	Right into Poor Farm Road. Quartz monzonite in walls and scattered outcrops.
112.2	Pass over Rte. 2. Crossed the probable position of the strand of the Clinton-Newbury fault zone that bounds the northwest side of the fault zone that bounds the northwest side of the fault sliver of Carboniferous(?) rocks at Pin Hill, about 1 mile to the southwest.
112.8	Left into Littleton Rd. Driving approximately along the southeastern margin of the Clinton-Newbury fault zone. Ridge to southeast, Oak Hill, is formed of Tadmuck Brook Schist.
113.2	Pull off road on left into dirt road, drive to end, 0.1 mile, and park. STOP 6, Mylonitized strand in the Clinton-Newbury fault zone. Outcrops and float of northwestern edge of Tadmuck Brook Schist around end of road. Walk northwest down ridge 120 m. Rocks at northwestern end of ridge are foliated porphyritic quartz monzonite and some pegmatite. Walk back along the outcrops at the southwest side of the ridge, observing the increasing amount of shearing and mylonitization eastward in the intrusive until it is an irregularly banded, chlorite rock. The sheared intrusive rock grades into the Tadmuck Brook Schist over 30 cm at the south end of outcrop on southwest side of gully. Continue driving east on Littleton Rd.
113.7	Pass over Rte. 2.

114.7	Littleton town line. Road changes name to Harvard Rd.
115.6	Outcrops of Tadmuck Brook Schist.
116.3	Continue straight across Oak Hill Rd. - King St. on what is here called Taylor St. Cross into upper part of Nashoba Formation, Beaver Brook Member.
117.5	Cross over Rte. 2 again and turn right into entrance Rte. 2 east, Concord - Lexington.
118.0	Pass under Rte. 495.
118.8-119.1	Nashoba Formation, gneiss outcrops; Long Pond Gneiss Member.
119.6-119.8	Nashoba Formation, schist, gneiss and marble outcrops of Fort Pond Member.
120.1	Pass West Acton exit.
120.3	Acton town line.
120.6-120.8	Nashoba Formation, gneiss, Fort Pond Member, cut by Andover Granite.
120.9-121.3	Nashoba Formation, gneiss of Nagog Pond Gneiss Member, cut by Andover Granite.
121.8	Nashoba Formation, gneiss, Nashoba Brook Member, cut by some Andover Granite.
122.3	Pass Rte. 27 exit to Maynard - Chelmsford.
122.6-122.7	Nashoba Formation, gneiss of Tophet Swamp Gneiss Member.
123.1	Cross Spencer Brook fault zone.
124.8	Concord town line. Marble-bearing zone in the Nashoba, crosses just to west. Nashoba Brook Member short distance ahead.
125.2	Outcrop on left side of Andover Granite.
125.3	Traffic circle. Continue east on Rte. 2
125.9	Cross Assabet River and Assabet River fault zone. Complex of Assabet Quartz Diorite and Andover Granite to east.
126.1	Left at signals, Rte. 2A east, to Concord center, and turn right in 50 m.

127.3	Veer left at junction with Main St.
128.1	Right onto Rte. 2A to Lexington Rd. at Concord center. Driving along base of delta.
130.0	Lincoln town line.
130.3	Veer left at road junction, dangerous corner.
132.7	Bloody Bluff on left.
132.8	Left into National Park parking lot, park, and walk back to Bloody Bluff. STOP 7, Bloody Bluff fault zone. Bluff exposes shattered Dedham Granodiorite that has undergone limonitic and chloritic alteration. Many fault surfaces are exposed, but highly sheared or mylonitized rock is uncommon here. The fault zone is at least 0.5 mile wide here. The bluff is a block bounded by a fault along the northwest side (which marks the contact between the Dedham and the Andover Granite to the west) and another fault along its southeast side. The latter fault passes through the southeast corner of the electric substation seen to the south. East of this fault, the Dedham is sheared to mylonitized and is crosscut by gabbro that postdates the shearing. The gabbro is well exposed along the powerline just south of the substation. Return to parking lot and walk east on footpath 50 m beyond footbridge, turn right into woods and go about 80 m, paralleling Rte. 2A, to roadcuts along a side road. Highly sheared Dedham crosscut by gabbro, part of Salem Gabbro-Diorite, which although not foliated is cut by later faults. Turn left from parking lot and continue east on Rte. 2A.
133.1	Gabbro here and in scattered outcrops to Rte. 128 has pendants, xenoliths, and xenocrysts of sheared to mylonitized Dedham.
133.2	End of field trip. Entrance to Rte. 128-South Shore; turn here for Rte. 2 or Turnpike for Boston or points south or west. Continue straight across Rte. 128 and turn right for Rte. 128 North Shore for connections to Rte. 3 and Rte. 1 for points north.

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Trips A-14 & B-14

THE PRE-SILURIAN EUGEOSYNCLINAL SEQUENCE BOUNDED BY

THE BLOODY BLUFF AND CLINTON-NEWBURY FAULTS,

CONCORD, BILLERICA, AND WESTFORD QUADRANGLES, MASSACHUSETTS

by

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The purpose of this field trip is to show representative exposures of the stratified rocks mapped mostly by D.C. Alvord in the Concord, Billerica, and Westford quadrangles, Massachusetts. The trip was prepared and is led by M.H. Pease, Jr., and R.J. Fahey; Alvord is unable to be present because of work commitments in Utah.

These stratified rocks have general northeast strikes and steep northeast dips. The rocks are within a broad regional imbricate fault system which trends northeastward across eastern Massachusetts (fig. 1) and which is bounded on the north and northwest by the Clinton-Newbury fault zone, a major structural feature of the region. The sedimentary and volcanic protoliths of these rocks were deposited mainly in a marine environment, probably near the margin of an eugeosyncline. The stratigraphic units (fig. 2) include the Marlboro Formation; Shawsheen Gneiss; Fish Brook Gneiss; the Nashoba Formation, which is divided into 10 members; and the Tadmuck Brook Schist. A report by Bell and Alvord (in press) presents definitions or redefinitions of these formations, locations of type areas, and detailed descriptions of stratigraphy, structure, and of lithology of the rocks.

The sedimentary and volcanic deposits that formed the rocks described in this paper accumulated and were deeply buried within a broad geoclinal basin. These flysch deposits have been regionally metamorphosed to kyanite grade and intruded by silicic to intermediate plutonic rocks, regional faulting has profoundly affected the distribution of stratigraphic units.
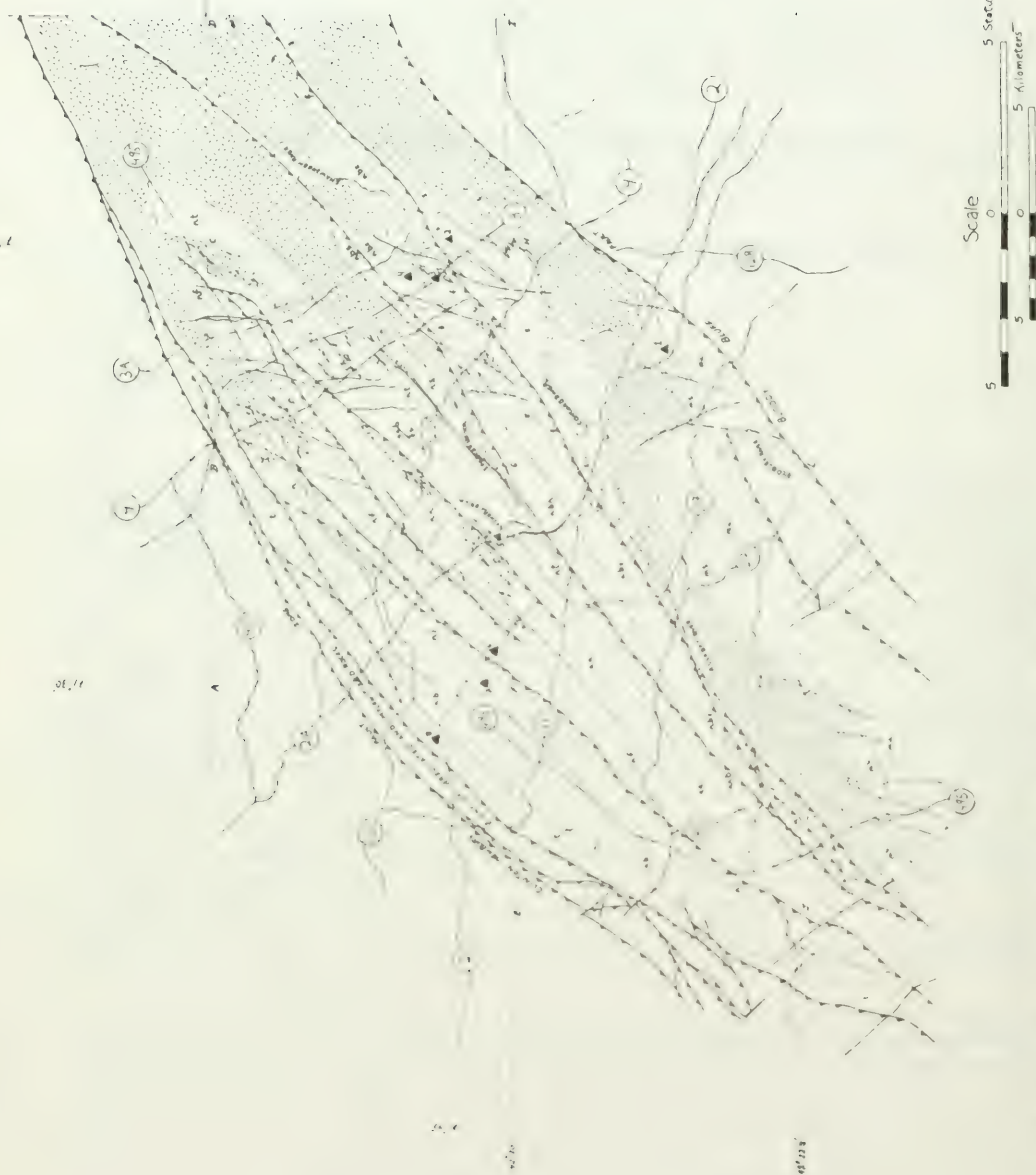
Fig. 1. Bedrock geologic map of the area between
the Clinton-Newbury and Bloody Bluff fault
zones, northeastern Massachusetts, showing
locations of stops for field trip

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CORRELATION OF MAP UNITS

[Andover Granite symbol] Andover Granite

Devonian (?)
or
older (?)

t	Tadmuck Brook Schist

NASHOBA FORMATION

	nb	Beaver Brook Member
	nl	Long Pond Gneiss Member
n	nf	Fort Pond Member
	nn	Nagog Pond Gneiss Member
	nnb	Nashoba Brook Member
	nt	Tophet Swamp Gneiss Member
	ns	Spencer Brook Member
	nbs	Billerica Schist Member
	nbh	Bellows Hill Member
	nbx	Boxford Member

f	Fish Brook Gneiss
s	Shawsheen Gneiss

MARLBORO FORMATION

ms	Sandy Pond Amphibolite Member
mu	Marlboro Formation, undivided

Pre-Silurian

Paleozoic (?)

SYMBOLS

——— —— —   contact of stratified rocks, dashed where inferred

— —— — —   fault

▲—▲—▲—▲—▲   thrust fault

◯110   route number

▲[8]   field trip stop

Fig. 2. Generalized stratigraphic column of the rocks between
the Bloody Bluff and Clinton-Newbury fault zones,
eastern Massachusetts

Tadmuck Brook Schist	920	
	1,580	Beaver Brook Member
	1,160	Long Pond Gneiss Member
	1,470	Fort Pond Member
	1,370	Nagog Pond Gneiss Member
	920	Nashoba Brook Member
	920	Tophet Swamp Gneiss Member
	580	Spencer Brook Member
	270	Billerica Schist Member
	1,100	Bellows Hill Member
	1,520	Boxford Member
Fish Brook Gneiss	1,520	
Shawsheen Gneiss	2,600	
	640	Sandy Pond Amphibolite Member
	1,500?	undivided

Nashoba Formation

Marlboro Formation

Marlboro Formation (2,140 m)

The Marlboro Formation consists of an upper Sandy Pond Amphibolite Member and an undivided part, which includes all the stratified rocks beneath the Sandy Pond, northwest of the Bloody Bluff fault. The undivided Marlboro is abundantly intruded by quartz diorite and diorite, which tends to crop out more readily than the country rock, which includes calc-silicate-bearing gneiss, quartzo-feldspathic mica gneiss, aluminous mica schist, quartzite, marble, and calc-silicate fels (Winkler, 1957) interstratified with both layered and massive amphibolite. The overlying Sandy Pond is chiefly thinly layered very fine grained amphibolite interlayered with massive medium-grained amphibolite. Other schists and gneisses amount to probably less than 20 percent.

The Sandy Pond Amphibolite Member can be traced from exposures in the town of Marlboro, northeastward across the Marlboro and Maynard quadrangles, and thence eastward into the Concord quadrangle through its type locality (STOP 1), to where this member and the undivided part of the Marlboro are cut out by the Bloody Bluff fault. This member can also be traced southwestward from Marlboro to the vicinity of the Wachusett-Marlboro Tunnel.

The top of the Sandy Pond is considered conformable and intergradational with rocks of the overlying Shawsheen Gneiss. The contact is placed where sillimanitic muscovite-biotite gneiss and schist greatly exceeds amphibolite. At many localities, the contact is intruded by a tongue of Andover Granite.

Shawsheen Gneiss (2,600 m)

The Shawsheen Gneiss consists of medium-grained locally sillimanitic muscovite-biotite-oligoclase-quartz gneiss and some lenticular bodies of bedded and massive amphibolite. Sulfidic sillimanite-mica schist is present near the base. The principal rock type is identical with the most common rock type in the Nashoba Formation, but the formation is separated from the Nashoba by the Fish Brook Gneiss.

About 1,000 m of strata representing most of the lower half of the Shawsheen Gneiss is best exposed in an area of scattered outcrops close to the Shawsheen River along Billerica Road in Bedford, starting with excellent outcrops 120 m due south from the intersection of Billerica Road with Page Road, thence northward along Billerica Road and side road for a distance of 1530 m. A section spanning about 1,100 m of strata that represent most of the upper half of the Shawsheen Gneiss is exposed at scattered localities (including exposures at STOP 2) along and near the Middlesex turnpike from a point beginning at the Assebet River crossing and going northwestward 1,450 m to the intersection with Lexington Road in Billerica, where the contact with the overlying Fish Brook Gneiss is mapped. About 1,250 m of the upper part of the Shawsheen Gneiss can be observed by traveling south and southeastward from the vicinity of Lane School (460 m west of Fawn Lake) in Bedford along a network of suburban roads delineated by North Road and Pine Hill Road on the west and Springs Road on the east, to where Pine Hill and Springs Roads intersect, an across-strike

distance of about 1,835 m. At this locality, the nearest exposures of Fish
Brook Gneiss can be seen by walking 60 m west from the north end of Lane
School Building to an excellent exposure of Shawsheen Gneiss where the strata
strike 35°, thence pace 170 m on a bearing of 30° to the first outcrop of Fish
Brook Gneiss on the northeast side of an abandoned railroad bed. At this
locality, the stream crossed enroute to the exposures of Fish Brook Gneiss
closely follows the faulted contact of these formations.

The top of the Shawsheen Gneiss is placed where its medium-gray medium-
to coarse-grained rocks are overlain by the generally very light gray, fine-
to medium-grained rocks of the Fish Brook Gneiss (Castle, 1965), which is
considered a formation by Bell and Alvord (in press). These formations are
presumed conformable, but wherever they have been mapped,there is a concealed
interval between the formations. Evidence for faulting is found at several
localities near the contact. Some of the rocks of the Shawsheen Gneiss were
included in the lower part of the Nashoba Formation of Hansen (1956), and some
were included in the Gospel Hill Gneiss of Hansen (1956).

Fish Brook Gneiss (1,520 m)

The Fish Brook Gneiss forms a distinctive and mappable unit amidst a
sea of drab metasedimentary units whose separation and mappability are fraught
with difficulty. The name Fish Brook Gneiss (Castle, 1965) is therefore
accepted with boundless waves of gratitude, and it has been assigned formational
status (Bell and Alvord, in press). Rocks of this formation in the Hudson and
Maynard quadrangle were included by Hansen (1956) in the lower part of the Nashoba
Formation.

The upper boundary of the Fish Brook Gneiss is drawn at the base of the
redefined Nashoba Formation. The contact is exposed at a small quarry 5,200 m
north-northeast of Nutting Lake. This quarry, hardly more than a trench, is
122 m northeast of the Billerica-Wilmington town line along Hopkins Street, and
about 9 m southwest of the street across a backyard at the edge of a woods. In
the exposure, very thin beds of dark-greenish-gray, very fine grained amphibolite
of the Boxford Member of the Nashoba can be seen interstratified with thin beds
of very light gray Fish Brook Gneiss.

Nashoba Formation (10,890 m)

The Nashoba Formation includes all metasedimentary and metavolcanic rocks
in the interval between the top of the Fish Brook Gneiss and the base of the
Tadmuck Brook Schist. It is divided into 10 members.

Relatively homogeneous members composed chiefly of medium-grained biotite-
oligoclase-quartz gneiss commonly containing muscovite and sillimanite alternate
with members of more heterogeneous lithology including fine-grained amphibole-
biotite gneiss and schist, amphibolite, locally sulfidic sillimanite-mica
schist, diopsidic calc-silicate fels and gneiss, and a few lenses of marble.

The lower contact of the Nashoba is gradational. Dark-greenish-gray mafic-rich beds of amphibolite or biotite-amphibolite schist of the Boxford Member grade downward into the very light gray mafic-poor beds of the Fish Brook Gneiss. The upper contact also appears gradational, where beds of amphibolite or medium-grained biotite gneiss of the Beaver Brook Member grade upward into beds of sulfidic sillimanite-muscovite schist of the Tadmuck Brook Schist.

Boxford Member (1,520 m)

The Boxford is composed of thinly bedded amphibolite, massive amphibolite, and biotite-amphibole gneiss and schist interlayered with subordinate amounts of biotite gneiss, calc-silicate bearing fels and gneiss, and rare lenses of marble. Locally, particularly at its type locality and in the vicinity of Nutting Lake in the town of Billerica, the lower part of the Boxford is made up almost entirely of amphibolite and amphibole-bearing gneiss and schist. Regionally, however, the member has been found similar to many of the overlying complexly interstratified members of the Nashoba.

The Boxford Member is well exposed in the vicinity of Nutting Lake (STOP 4) in the town of Billerica. Exposures of mostly thin-bedded, very fine grained amphibolite are abundant across a 460-m-wide belt on the northwest side of this lake. On its southeast flank, the unit is separated from the underlying Fish Brook Gneiss by a tongue of Andover Granite, and some of the lower part of the Boxford is presumed missing. The upper part of the Boxford is not well represented in this area, but some good exposures of these rocks are found along suburban roads leading both northeast and southwest from junctions on Boston Road, about 1,225 m due north of the northeast end of Nutting Lake, or 1,225 m south of Billerica Center along Boston Road.

The Boxford also is well represented within a belt of exposures delimited on the northwest by the southeast shore of Batemans Pond, and on the southeast by a line between Farmers Cliff and Hubbard Hill. Rocks exposed in this area include every lithology attributable to the Boxford, including limestone, but varieties of amphibolite predominante slightly. From this reference locality, the belt can be easily followed northeastward some 3,100 m to Bedford Road in Carlisle, whence exposures are rare. It can also be easily traced southwestward some 4,300 m to Nashoba Brook at the southern end of the type locality of the Nashoba Formation. Here, rocks of the Boxford Member are fairly well exposed in a 600-m-wide belt immediately north of Warners Pond and east of Nashoba Brook in West Concord.

The upper boundary has not been seen in outcrop but attitudes of the strata are conformable, and intertonguing of rock types suggest that the contact is gradational. The amphibole-bearing gneiss and amphibolite of the Boxford apparently intertongue with and grade upwards into biotite gneiss that is predominant in the Bellows Hill Member.

Bellows Hill Member (1,100 m)

The Bellows Hill Member is almost entirely medium-grained sillimanitic muscovite-biotite gneiss that typifies the Nashoba. Subsidiary fine-grained amphibole-biotite gneiss and amphibolite and thin lenticular beds of marble

and related diopside-tremolite-calc-silicate fels occur discontinuously in the upper half.

The Bellows Hill Member is best exposed 2,600 m southwestward 220°, from Bellows Hill in the town of Carlisle and on the south and west of the Bemis estate, in the town of Concord. Excellent exposures of the middle part of this member are also present in a belt of exposures extending some 1,800 m northeastward from South Acton center.

The top of the member is not exposed. It is presumed conformable and intergradational, its biotite gneiss intertongued with and grading upwards into the sulfidic sillimanite-mica schist of the Billerica Schist Member. Wherever the member has been mapped, however, there is a concealed interval between the units, along which at many localities, evidence for faulting has been found.

Billerica Schist Member (270 m)

The Billerica Schist Member consists chiefly of varieties of sulfidic sillimanite-muscovite-biotite schist and subsidiary lenticular bodies of amphibole schist and hornblende-biotite schist and gneiss.

Best exposures of the Billerica Schist Member occur on the southeast side of Fox Hill and along the course of the Concord River between its crossing by U.S. Route 3 southwestward to the vicinity of Riverside, all in the town of Billerica. It has been traced with considerable difficulty northeastward just inside the Wilmington quadrangle and southwestward nearly to Nashoba Brook in Acton, a total distance of about 15.3 km.

This member everywhere is separated from the overlying member either by a concealed interval at least 100 m wide or by a tongue of Andover Granite. The contact is presumed to be conformable.

Spencer Brook Member (580 m)

The Spencer Brook Member consists of complexly interstratified thin-bedded amphibole-biotite gneiss, thinly bedded amphibolite, and massive amphibolite, and notable amounts of amphibole-diopside calc-silicate fels and gneiss, biotite gneiss, and some thin lenses of marble.

The rocks of this member are generally well exposed, forming an outcrop belt ranging from 600 to 750 m in width over most of its mapped extent. The unit is readily traced from its type locality northeastward 6,100 m to the west side of Winning Pond in Billerica, where it is lost in or cut off by Andover Granite, and southwestward some 6,000 m across Nashoba Brook to where it is evidently cut out by the Spencer Brook fault about 750 m south of Acton Center. Along this belt, the rocks of the Spencer Brook Member are best represented in the area between Strawberry Hill and the Acton-Carlisle town line in Acton and the area between West Street and Hemlock Hill in Carlisle.

The generally amphibole-bearing and calc-silicate-bearing rocks of the Spencer Brook intertongue with and grade upwards into the rocks of the Tophet Swamp Gneiss Member, which are chiefly medium-grained biotite gneiss.

Tophet Swamp Gneiss Member (920 m)

The Tophet Swamp Gneiss Member is chiefly the medium-grained sillimanitic muscovite-biotite-oligoclase-quartz gneiss characteristic of the Nashoba, containing a few lenticular bodies of thinly bedded amphibolite and massive amphibolite. This generally well exposed member is especially accessible in Carlisle along Cross Street from its junction with South Street northward about 1,200 m, from Carlisle Center northwestward for about 1,600 m along Westford Street and northward for about 1,650 m along Lowell Street. Its outcrop belt, mostly 900-1200 m wide where mapped, can readily be followed from Carlisle Center northeastward 15.3 km into the town of Tewksbury, where its most northeasterly exposures can be seen just west of Ames Hill. The unit has been cut off northeast of Ames Hill by intrusion of Andover Granite, and by faulting.

The medium-grained biotite gneiss of the Tophet Swamp intertongues with and grades upward into the complexly interstratified amphibole-bearing and calc-silicate bearing rocks characteristic of the lower part of the Nashoba Brook Member.

Nashoba Brook Member (920 m)

The Nashoba Brook Member is a heterogeneous assortment of amphibole-biotite gneiss, diopsidic calc-silicate gneiss and fels containing amphibolite in the upper and lower parts. The middle part is chiefly sulfidic sillimanite-biotite-muscovite schist and gneiss and amphibolite and biotite gneiss.

The member is exposed at North Acton center, on the hill beginning about 325 m south-southeast of North Acton center and on the west side and close to Nashoba Brook; on the east side of Nashoba Brook at localities 760 m and 1,100 m due south of North Acton center; and on both sides of Nashoba Brook 610 m due east of North Acton center, all in the town of Acton. These exposures, in the aggregate, represent well the rocks of the member. Its rocks are also well displayed in the town of Carlisle, about 3,000 m northeast of North Acton center, especially at hills, respectively, 50° and 450 m and 115° and 450 m from the intersection of Acton Street and West Street. Where mapped, the rocks of this member form a northeast-trending belt of scattered outcrops 1,200 m wide. The member has been traced from its type locality in Acton southwestward about 4,600 m and northeastward 8,700 m to the southwest end of Russell Mill Pond in the town of Chelmsford. Here, the member evidently is cut off by two or more north-trending cross faults and is shifted north-northeast to where it is lost and concealed in a maze of complex structure and Andover Granite. Mapping indicates that the upper contact is conformable and gradational the amphibolite and calc-silicate rocks of the Nashoba Brook are intertongued with and grade upwards into the biotite gneiss that is predominant in the Nagog Pond Gneiss Member.

Nagog Pond Gneiss Member (1,370 m)

The Nagog Pond Gneiss Member is chiefly the medium-grained muscovite-biotite-oligoclase-quartz gneiss that characterizes the Nashoba Formation. This dominant lithology is interstratified with some amphibole-biotite gneiss and lenticular bodies of thinly bedded amphibolite and massive amphibolite.

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An area of good exposure of the Nagog Pond Gneiss Member is bounded on the northwest by Nagog Pond, on the southwest by Nagog Brook, on the southeast by the only southward-flowing tributary to Nagog Brook, and on the northeast by Great Road, all in the town of Acton. Within this area, rocks of the lower two thrids of the Nagog Pond Member are fairly well represented. Excellent exposures are also present in the town of Chelmsford south along Concord Road from its crossing of Farley Brook to the Chelmsford-Carlisle town line, and westward off Concord Road on a network of residential roads. The rocks exposed in this area represent the upper two-thirds of the Nagog Pond, the lower third is cut out on the southeast by an inferred fault. The rocks of the Nagog Pond form a belt that ranges in width from 1,400 to 2,000 m, the wider parts of which coincide with abundant sills of Acton Granite. This erratically exposed member has been traced from Nagog Brook southwestward about 3,000 m to Route 2, from which it evidently continues for some distance; it has been followed northeastward a little more than 10 m to Concord Road in Chelmsford. Farther northeast, rocks tentatively assigned to the Nagog Pond are sparsely and wildly distributed in an area dominated by the intrusion of granite and made complex by faults.

The upper contact with the Fort Pond Member has not been seen, the width of concealment between the units ranging from a minimum of 150 m to several times that width. Strata within the two units are mostly parallel, and the contact is parallel over a distance of at least 15 m. The medium-grained biotite gneiss of the Nagog Pond intertongues with and grades upward into the complexly interstratified biotite-amphibole gneiss, amphibolite, and calc-silicate-bearing (diopside-tremolite) rock of the Fort Pond Member. On these bases, the contact is considered conformable and gradational.

Fort Pond Member (1,470 m)

The Fort Pond is one of the members with varied lithology. The lower part is made up mostly of fine-grained amphibole-biotite gneiss, calc-silicate (diopside-tremolite)-bearing gneiss or fels, and amphibolite. The upper part consists chiefly of the same rock as the lower part but includes, in addition, some sulfidic sillimanite-mica schist and discontinuous beds of marble.

The lower third of the Fort Pond Member is particularly well exposed in the area from between the southeast shore of Fort Pond extending southeastward about 600 m to Fort Pond road, which nearly coincides with the lower, south-eastern, boundary of the member. This same group of rocks is more conveniently observed in roadcuts along Route 2 by starting from a rock-cut on this route, 920 m due south from the southern tip of Fort Pond, and thence going northwest-ward over a total distance of 610 m. Fair exposure of the middle part of the unit is found in the area extending roughly from the north and northwest shores of Fort Pond northward and northwestward to Nashoba and Boxboro-Newtown Roads. Very excellent exposures of the upper third of the member begin 765 m due west of the southwest corner of Fort Pond, continue westward across Route 2 to the Boston and Maine tracks at Boxboro Station on the northeast side of the tracks, along both sides of Route 3, and are formed in the woods and fields between these two routes. Boxboro Station sits almost athwart the contact of the Fort Pond Member with the overlying Long Pond Gneiss Member, the nearest good exposure of Long Pond rock occurring in a string of outcrops that begin about 120 m southwest of the station on the southeast side of Depot Road.

The Fort Pond Member is also well exposed at Robbins Hill, about 12 km northeast of Fort Pond, in the town of Chelmsford. Within this area, an excellent representation of the Fort Pond Member can be observed by starting at the forks of Farley Brook and thence zigzagging from crop to crop on an average bearing of 335° across the top of Robbins Hill and on to Interstate 495, a straight-line distance of 2,450 m. The rocks of this member form a northeast-trending belt that ranges in width from 1,500 to 2,450 m; the wider parts are mostly where conformably emplaced sill-like bodies of granite or structural complexities have been seen. This belt of rocks has been mapped from its type locality at the southwestern corner of the Westford quadrangle, northeastward a little more than 16 km to the vicinity of North Road and Boston Road in Chelmsford Center. From here, northeastward, the rocks of the unit are lost under glacial deposits which cover its northwesterly course for a distance of more than 5 km to southeastern Lowell and northern Tewksbury. At this locality, rocks of the Tadmuck Brook Schist appear in scattered outcrops on the north; scattered outcrops of gneiss, schist, and amphibolite having wildly diverse attitudes and considered almost certainly to correlate with the underlying Nagog Pond Gneiss and Nashoba Brook Members, together with much Andover Granite, appear to the east and south of the projected course of the Fort Pond Member.

With the aid of Hansen's geologic maps of the Hudson and Maynard quadrangles (1956), the Fort Pond Member has been traced from its type locality southwestward 11 km to the town of Bolton. The outcrop belt narrows to less than 1,500 km near East Bolton.

The upper contact is believed to be conformable and gradational, the generally complexly interlayered amphibolite, calc-silicate-bearing gneiss, and sillimanite-mica schist of the Fort Pond intertonguing with and grading upward into the medium-grained biotite gneiss that is predominant in the Long Pond Gneiss Member. At many localities, the contact is faulted.

<center>Long Pond Gneiss Member (1,160 m)</center>

The Long Pond Gneiss Member consists mostly of the characteristic medium-grained sillimanitic muscovite-biotite-oligoclase-quartz gneiss of the Nashoba interstratified with a few lenticular bodies of thinly bedded amphibolite and massive amphibolite.

Scattered but good and representative exposures are found within a 1,530-m wide belt that extends from the southwest shores of Long Pond south-westward some 3,000 m to the southern and western borders of the Westford quadrangle and the vicinity of Boxboro station in the town of Boxboro. The southeast, lower boundary of the Long Pond Gneiss Member is almost coincident with a line connecting the eastern edge of Long Pond with the crossing of the Boston and Maine Railroad tracks by Depot Road at Boxboro Station in the town of Boxboro. The most complete section and the bulk of the outcrops in the area are along Route 2 and the adjacent Boston and Maine tracks (STOP 7).

Although not generally well exposed, the Long Pond Gneiss Member has been mapped from its type locality northeastward, on a consistent bearing of 40°, about 12.5 km to the junction of the forks of Tadmuck Brook in the town of Westford and close to the Westford-Chelmsford town line. The trace of these two forks, bearing 60°, is coincident with the lower contact of the Tadmuck Brook Schist. Northwest of these forks, the Tadmuck Brook Schist is exposed at

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several places, showing rather consistently strikes of 60° and dips of 80°
NW. At present, it is not certain whether this truncation, represented by
a 20° divergence of strike between the units, is the result of faulting or
of a disconformity. With the aid of Hansen's geologic maps of the Hudson and
Maynard quadrangles, the Long Pond Gneiss Member has also been traced south-
westward from its type locality about 9.8 km to Rattlesnake Hill in the town of
Bolton. Here, its outcrop belt of mostly sillimanitic biotite gneisses has
narrowed down to about 1,250 m.

The upper boundary is assumed to be conformable and gradational, its
medium-grained sillimanitic biotite gneisses intertonguing with and grading
upwards into the complexly interstratified amphibole-bearing and calc-silicate
rocks characteristic of the lower part of the Beaver Brook Member.

Beaver Brook Member (1,580 m)

The Beaver Brook Member is the uppermost member of the Nashoba and is
composed of a heterogeneous variety of rock types, chiefly amphibole-biotite
gneiss, calc-silicate (tremolite-diopside)-bearing gneiss and fels, amphibolite,
and rare discontinuous beds of limestone in the lowermost 400-500 m. The upper
part includes medium-grained sillimanitic muscovite-oligoclase-quartz gneiss
complexly interstratified with sulfidic sillimanite-muscovite-biotite-oligoclase-
quartz schist, thin-bedded and massive amphibolite, and amphibole-biotite gneiss.

Representative exposures of the member occur in an area roughly bounded
on the northeast by Mill Road in Littleton, on the southeast by Forster Street
in Littleton and Hill Road in Boxborough, on the southwest by Littleton County
Road in Harvard and Route 111 (Old Turnpike) in Boxborough, and on the north-
west by the foot of Oak Hill in the towns of Harvard and Littleton. Oak Hill
is underlain by rocks of the Tadmuck Brook Schist, and the foot of this hill
coincides almost exactly with the upper boundary of the Beaver Brook Member.
For the most part, the strata of both units strike about 40° and dip steeply
to the northwest. Within this area, rocks of the approximate uppermost and
lowermost thirds of the unit are generally well exposed; rocks of the middle
thrid of the unit are represented by only a few exposures at the southwest end
of the area and at Mill Pond on the northeast.

The Beaver Brook Member has been mapped from Mill Road in Littleton about
7.6 km northeastward on a bearing of 40° to the vicinity immediately south of
Westford Center and Prospect Hill, all in the town of Westford. Here, as at
the northeastward termination of the Long Pond Gneiss Member, the rocks of the
Beaver Brook are truncated by the more east-trending rocks of the Tadmuck Brook
Schist. Here the schists of the Tadmuck Brook (well exposed west and southwest
of Westford center) mostly strike 55°-65° and dip 80°-90°, mostly northwest.
With the aid of Hansen's geologic map of the Hudson quadrangle (1956) the
Beaver Brook Member has also been traced from Mill Road southwestward 14.5 km
to Bolton Center, where the unit is about 1,700 m wide at the surface.

The upper contact of the Beaver Brook Member with the Tadmuck Brook Schist
is exposed on Littletown Road at the foot of Oak Hill, just northwest of the
Oak Hill Road intersection. The contact appears to be conformable and grada-
tional at this locality. Thin-bedded amphibolite intertongues with sillimanite-
biotite-quartz-muscovite schist of the Tadmuck Brook. Northeastward along the

base of Oak Hill the strata of both formations strike about 40° and dip steeply northwest. The regional northeastward overlap of the Tadmuck Brook onto successively lower members of the Nashoba Formation, however, suggests the possibility of unconformity.

Tadmuck Brook Schist (920 m)

The Tadmuck Brook Schist is chiefly phyllite in the upper part, sericite-staurolite-andalusite phyllitic schist in the middle part, and sillimanite-quartz-mica schist in the lower part, all interstratified with lenticular bodies of thin-bedded to massive amphibolite.

The formation is exposed on both sides of Tadmuck Brook in the town of Westford. The area of exposure is well delineated on its southeast by the upper forks of Tadmuck Brook, which here coincide with the lower boundary of the schist unit, and on the northeast by Lowell Road, here coinciding closely with the upper boundary of the unit. The area is arbitrarily bounded on the northeast by Chamberlain Road and on the southwest by Providence Road. The best representation of the unit in this area is found among exposures on the hill immediately southwest of the main branch of Tadmuck Brook, between Lowell Road and Main Street. Excellent reference localities of the Tadmuck Brook Schist are 2,300m northeast (55°) of Tadmuck Brook along and near School and Westford Streets between Graniteville and Locke Roads, all in Chelmsford, and 4,100 m southwest (235°) of Tadmuck Brook along and near Hartford Road between Patten and Robinson Roads, all in Westford. The Tadmuck Brook Schist has been traced between the city of Lawrence on the northeast and the vicinity of Shrewsbury on the southwest, a distance of about 68 km. The Tadmuck Brook is also well exposed on Oak Hill in the Ayer quadrangle, STOP 8, where it consists almost entirely of rusty-weathering sulfidic, graphitic, micaceous, staurolite schist.

The pelitic schist of the Tadmuck Brook locally intertongues with and grades downward into the comparatively mafic-rich quartzo-feldspathic gneissose rock of the Nashoba Formation. Regionally along this boundary, however, commencing from about the Littleton-Westford town line and thence northeastward to the vicinity of Lawrence, where the Tadmuck Brook Schist is lost, the units of the Nashoba are truncated at low angle by the overlying pelitic schist of the Tadmuck Brook, and a reasonable case for a disconformity can be made, but, in places, this contact is known to be a fault.

The top of the Tadmuck Brook Schist is everywhere cut out by faults here considered to belong entirely to the Clinton-Newbury fault zone. This fault zone contains broken, slivered, and milled rock consisting of quartz and phyllite belonging to the Merrimack Group of gneiss; schist from the Tadmuck Brook Schist, and of granitic and mafic igneous rock broadly related to the Ayer Granodiorite and so-called "Chelmsford Granite". The fault zone is more than 1,500 m wide in the Hudson and Ayer quadrangles and progressively thins northeastward; it is difficult to recognize northeast of Lawrence. Many faults evidently related to the Clinton-Newbury faulting lace through the aluminous schists of the Tadmuck Brook, cutting it at high angles, and contribute to the discontinuity and irregular distribution of its rock types.

Road Log for Trip A-14

Field trips starts at 8:00 A.M. sharp in the Boston University parking lot.
Drive west on either Route 2 or Route 90 to 128. The zero starting point for
this log is at the west side of the Route 128 overpass on Trapelo Road.

Mileage

0.0   Entrance to L.F.E. building on Trapelo Road. Drive west
                on Trapelo.

0.7   Road crosses narrows of Cambridge Reservoir

2.5   Town of Lincoln intersection Trapelo Road and Bedford Road.
                Continue west on Sandy Pond Road.

2.9-3.1   Turn right at entrance to Cordova Museum; continue bearing
                right for 0.2 mi to parking lot. Leave bus and walk west
                back along road. Outcrops on lawn to the north are STOP 1.

                STOP 1. The Sandy Pond Amphibolite Member of the Marlboro
                Formation crops out well and is a conspicuous marker in
                this part of the section. Exposures consist mostly of
                thick even-layered greenish-gray to greenish-black fine-
                grained amphibolite. Thin felsic laminae accentuate the
                compositional layering. Partings range from paper thin
                to almost a metre thick.

3.1-3.7   Return to bus. Bus returns to Lincoln center crossroads
                again.

3.7-4.0   Travel east on Trapelo Road to Lexington Road. Turn left,
                leaving cemetary on right.

4.0-5.3   Lexington Road

5.3-5.4   Lexington Road is almost directly on a trace of the Bloody
                Bluff fault. Low light-gray outcrop on right side of bus
                is a mylonitized granite rock commonly found along the trace
                of the fault.

5.4   Turn right onto Route 2.

5.4-6.6   Travel east on Route 2; and turn right at entrance to Route
                128 North.

6.7-11.4   Drive north and northeast on Route 128;

11.4   Take Route 3 exit. Keep to right after exit to avoid
                getting on Route 3-A

12.7	The trace of the Bloody Bluff fault is in the valley that the highway crosses here. Trace is more easterly than at Route 2.
13.7	Turn right at Exit 26.
14.1	Turn right from exit ramp onto Route 62.
14.1-14.5	Traveling east on Route 62.
14.6	Turn left on Middlesex Turnpike
16.5	STOP 2. Examine outcrops exposed for about 500 m on both sides of Middlesex Turnpike. This is a representative exposure of the Shawsheen Gneiss. Rock is a gray-weathering quartz-feldspar-biotite gneiss. Muscovite is conspicuously patchy in this formation, although it is not well shown here except in the northern outcrops or the west side. As explained in the introduction, this rock type cannot be distinguished from the most common rock type in the Nashoba Formation, but the Shawsheen is separated from the Nashoba by the distinctive Fish Brook Gneiss. Note contortion of the foliation and compositional banding. Also note chlorite, epidote, and slickensides on most fractures.
16.5	Buses continue north on Middlesex Turnpike.
16.9	Intersection with Lexington Road. This is the approximate trace of the contact with the Fish Brook Gneiss, not exposed.
17.1-17.4	Turn left on Manning Street and drive to end of pavement. Leave bus and walk along dirt road for about 0.3 mi. STOP 3: The outcrops for STOP 3 are roadcuts along Route 3. This is a heavily traveled road, so be careful. The best exposure extends for about 250 m on the east side; there is no need to cross the pavement. The Fish Brook is a light-gray felsic gneiss. Layering and compositional banding are weak and widely spaced. Biotite, generally amounting to less than 15 percent, defines the foliation, which is characteristically crinkled. Muscovite is rare to absent. Note presence of rusty schist layers. Note presence of diabase dike pair, not observed across the road. Slickensides on joints are nearly horizontal or plunge gently to the southwest. Return to bus. If time permits, examine the natural exposures of Fish Brook on the hillside north of the dirt road.
17.4-17.7	Return to Middlesex Turnpike

17.7-18.6	Turn right and travel north on Middlesex Turnpike to the top of the hill just north of Nutting Lake.

STOP 4: Boxford Member of Nashoba Formation. The Boxford is one of the Nashoba members characterized by hetero-geneity and a predominance of amphibolite.
In this outcrop well-layered evenly layered light- to dark-greenish-gray color-banded calc-silicate-bearing amphibolite lies stratigraphically above rusty-weathering sulfide-rich calc-silicate-bearing schist. |
18.6-19.3	Continue north on Middlesex Turnpike to its end. Turn left on Concord Road.
19.8	Cross Route 3, continue west on Concord Road.
20.5	Turn right on Dudley Road (unmarked)
21.0	Turn right on Nashua Road, cemetery on left-hand corner.
21.5	Cross Concord River
21.8-22.1	Outcrops of Andover Granite
22.5	Turn left on Treble Cove Road
23.5	Turn left on Maple Street - Exposure of Andover Granite on left.
23.6	Bear right on Brook Street.
24.8	End of Brook Street; turn right on Bedford Road, Route 225.
25.9	Center of Carlisle; continue west on Route 225. Tophet Swamp Gneiss Member exposed on right. Graded bedding indicates tops to west.
27.4	Turn left on Acton Street - right at east border of the West-ford quadrangle.
28.3	Junction Acton Street with Route 27, Main Street. Drive south on Route 27.
29.8	Railroad crossing
30.7	Turn right at entrance to Wampus Heights Apartments. Turn right and proceed uphill into parking lot.

STOP 5: lunch stop. Facilities should be available at several gas stations at the road intersection 100 m away. |

Amphibolite-bearing gneiss of the Nashoba Brook Member
are well exposed in the hills west and northwest of the
parking lot. At parking lot level, the gneiss is more
felsic and somewhat pelitic like the quartz-feldspar-
biotite-muscovite gneiss characteristic of the more homo-
geneous members of the Nashoba Formation. These felsic
rocks crop out in the woods to the northwest and apparently
form the eastern scarp of outcrop. Back of the scarp, thickly
bedded amphibolite predominates. This amphibolite gneiss is
very different from the amphibolite in the Boxboro Member of
STOP 4. It is more massive, less evenly layered, coarser
grained, and calc-silicate minerals are not conspicuous. At
the top of the ridge is somewhat finer grained more thinly
layered amphibolite that extends to the southernmost ex-
posures just north of the condominiums.
Stringers of gneissic intrusive rock as much as several
metres thick parallel the layering and locally are difficult
to distinguish from the felsic country rock.

30.7   Leaving parking lot, turn right, west, on dirt road that
            joins Route 119.

30.8   Turn right and drive northwest on Route 119, Great Road.

32.1   Nagog Pond on left.

32.3   Turn left on Nashoba Road, north side of Nagog Pond.

33.5   Cross Nagog Hill Road.

34.1   Junction Nashoba Road on New town Road. Bear left on
            Newtown Road.

34.7   Fort Pond Member of Nashoba Formation exposed over crest
            of hills, right side of road.

35.0   Bear right where sign says "Not a through road." This is
            the old Boxboro Road and leads to exposures of the Fort Pond
            Member in roadcuts along Route 2.

35.5   STOP 6: Fort Pond Member of Nashoba Formation. Exposures
            are best on the northeast side of this well-traveled high-
            way. Do not cross pavement. The country rock in this out-
            crop varies from limy sulfidic schist, through coarse calc-
            silicate bearing gneiss to dirty calc-silicate-bearing marble.

            Note that the alternation of lithology, particularly rusty
            and nonrusty, can be matched across the highway. If the
            strikes are not warped, there is a suggestion of a few metres
            of offset, the west side outcrops having moved south.

In the exposures south of the parking area, almost 50 percent of the exposures are intrusive, mostly sills of porphyritic and nonporphyritic Ayer Granodiorite. Also includes fine-grained 2-mica granite gneiss and coarser grained, gneissoid pegmatite. Note that these crosscut as well as parallel the layering.

35.5-35.9   Return to first right. This is a sharp turn for a bus, but better than turning into the more traveled road further along.

36.2   Turn right again

36.5   Pass under Route 2

37.1   Make sharp right onto Littlefield Road

38.4   Railroad crossing at Boxboro Station. Go straight uphill.

39.0   Long Pond Gneiss Member of Nashoba Formation exposed on west side of road.

39.3
STOP 7   Park at edge of field and walk north beyond outcrop at edge of field to railroad tracks. Walk southeast about 200 m along tracks to railroad cuts. Exposures in woods on either side of track for about 400 m are representative of the Long Pond Gneiss Member. This is the most common lithology of the Nashoba Formation and is characteristic of the homogeneous gneiss members.

39.3-39.7   Continue west to end of Littlefield Road. Turn right on Foster Street.

40.1   End of Foster Street; turn right on Taylor Street.

40.1-41.7   Continue on Taylor Street, crossing by overpass of Interstate 495 and of Route 2, to the town of Littleton.

41.7   Turn left in front of Citgo Station on King Street

41.8   Bear right and continue uphill; road turns left to run subparallel to large outcrops of sulfidic schist of STOP 8.

43.0   Park beyond southwest end of outcrop. Walk back along road to observe excellent exposures of the sulfide-graphite-bearing facies of the Tadmuck Brook Schist. The lower 300 m of the Tadmuck Brook Schist from here on Oak Hill to where the formation crosses Route 2 is composed almost entirely of this highly sillimanitic biotite-quartz-feldspar schist.

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CATACLASTIC AND PLUTONIC ROCKS WITHIN AND WEST OF THE CLINTON-NEWBURY FAULT ZONE, EAST-CENTRAL MASSACHUSETTS

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Introduction

This trip will examine the Clinton-Newbury fault zone and adjacent rock units exposed in the southern two thirds of the Ayer 7½ minute quadrangle, Massachusetts.

The Clinton-Newbury fault zone is the dominant geologic feature of this area. It separates and includes contrasting lithologic elements. West of the zone, the bedrock is dominated by the Ayer Crystalline Complex(Gore, 1976), a series of closely related, predominantly felsic plutonic rocks, and a series of clastic metasediments. East of the zone is the Tadmuck Brook Schist(Bell and Alvord, 1974), a series of clastic and volcano-clastic(?) rocks. A fault sliver containing the type locality of the Harvard Conglomerate exists within the wide imbricate zone in the vicinity of Harvard Center.

Tadmuck Brook Schist

The Tadmuck Brook Schist is a rusty schist unit that can be traced continuously from Shrewsbury to Lowell Massachusetts. The unit is a coarse muscovite schist containing varying amounts of biotite, quartz, pyrite and sillimanite or andalusite. Secondary sulfates may be found along joint surfaces. Thin beds of semipelitic rock are often present.

In weathered outcrops this unit displays a distinct rusty brown color. This distinct appearance has led some workers to assume that a time equivalence exists between many of these euxinic schists at different locations in New England.

Clinton-Newbury Fault Zone

The Clinton-Newbury fault zone shows considerable variation in width and character where it crosses Harvard and Littleton Massachusetts. The zone is between 3000 to 5000 feet wide in the vicinity of Harvard Center and is characterized by Protomylonite(?), blastomylonite, mylonite gneiss, and narrow zones of mylonite or mylonite schist. These cataclastic units grade into or sharply cut the large slivers or blocks of plutonic and metasedimentary material that dominates the bulk of this zone.

Two miles to the northeast of Harvard Center the fault zone narrows to less than 800 feet wide and contains both finely

laminated and nonlaminated mylonite and blastomylonite.

The zone widens again so that in Littleton, 2.4 miles further northeast, it is over 2000 feet wide and is dominated by mylonite gneiss, blastomylonite and minor mylonite schist. None of the finer grained cataclastic rocks seen here show the pronounced fine laminations seen in the narrow segment of the fault zone.

Harvard Conglomerate at Pin Hill

The Harvard Conglomerate at Pin Hill has been the subject of much debate in arguments concerning regional correlation. Emerson(1917), Jahns(1952) and Hansen(1956) all dated the surrounding units of the Ayer Crystalline Complex as Pennsylvanian or post Pennsylvanian based on their belief that the Harvard Conglomerate was intruded by these plutonic units.

Grew and Robinson(in Grew,1973) interpreted the contact on the west side of Pin Hill as an unconformity.

During the mapping of the Ayer quadrangle(Gore, in preparation), it was discovered that a narrow zone of cataclastic rock occasionally accompanied by silicification separates the Harvard Conglomerate from plutonic rocks on the east side of Pin Hill. The conglomerate on the west side of Pin Hill is also separated by a fault(Gore, 1976) from the adjoining plutonic rock but the zone of cataclasis is narrow and silicification is not as prominant as on the east side. These faults appear to be splays of the Clinton-Newbury fault zone.

The presence of these faults does not necessarily preclude the earlier interpretations as major slippage along contacts is not uncommon. However, the presence of similar cataclastic rock on three sides of Pin Hill(east, west and north) strongly suggests that on a macroscopic level the Harvarvard Conglomerate at Pin Hill is a fault splinter.

Ayer Crystalline Complex

The Ayer Crystalline Complex lies in a belt which runs southwest to northeast through the center of the Ayer quadrangle. The rocks vary in composition from quartz diorite to granite, with the majority of the rocks falling within the narrow composition band between granite, close to the quartz monzonite boundary, to granodiorite.

The complex is composed of three major facies, the Clinton Quartz Monzonite, the Devens-Long Pond Gneiss and the Chelmsford Granite.   Other facies exist but these generally appear to be border and/or residual phases directly related to the three major facies.

Within this belt are rock bodies, some of significant size
(mappable on a 1:24,000 base), such as fine grained, banded
biotite gneiss and quartz diorite. The relationship of these rocks
to units of the Ayer Crystalline Complex is still uncertain.

Clinton Quartz Monzonite: The predominant subfacies is a
porphyritic, slightly to moderately foliated, coarse-grained
rock. Local zones of intense foliation have been observed.

The megacrysts are microcline microperthite averaging 5 cm
in length with 10 cm lengths not uncommon. The other major min-
erals are saussuritized plagioclase(albite to sodic oligoclase),
quartz, and biotite. Accessory minerals are apatite, zircon, an
un unidentified opaque, sericite, muscovite(well developed flakes),
epidote, allanite, clinozoisite(?), chlorite, and a carbonate
mineral.

A nonporphyritic border phase occures as a subfacies.

Devens-Long Pond Gneiss: This facies shows considerable
textural variation but is dominated by two major textural types.

One textural type is a "porphyroblastic" gneiss containing
microcline microperthite averaging 1 to 2 cm in length. Albite,
quartz, and biotite are the other major minerals. Chlorite,
sericite, sphene and an opaque mineral are usually present.
Commonly present are zircon, apatite, muscovite(well developed
flakes), a carbonate mineral, and limonite. Allanite and tour-
maline occur more rarely. These rocks are predominantly of
quartz monzonite composition but can range into the granodiorite
field.

The other textural type is a more equigranular rock, gen-
erally gneissic. The dominant minerals are quartz, albite and
biotite. Microcline, sphene and allanite are common in most of
these rocks. Blue-green pleochroic amphibole(actinolite?),
sericite, epidote, zircon, apatite, garnet, tourmaline(?), and
chlorite are frequently present. This textural subfacies varys
more widely in composition cantaining rocks of quartz monzonite,
granodiorite, trondjemite, and quartz diorite composition.

Chelmsford Granite(Quartz Monzonite): This unit is essential-
ly Currier's(1937) Chelmsford Granite. It is included in the
Ayer Crystalline Complex because of its close geographic, textural
and mineralogical similarities to the other rocks of the complex.
The minerals, quartz, microcline, plagioclase(An 5-13), muscovite
(will developed flakes), biotite or chlorite(both generally less
than 5% of the rock), constitute the major phases. Epidote, zircon,
sphene and garnet are common accessories.

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Generalized Geologic and location map of the southern
portion of the Ayer 7½ minute quadrangle, Massachusetts.

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<u>ROAD LOG</u>

All stops on this trip are located on the Ayer 7½ minute quadrangle, Massachusetts.

This trip begins at the first rest area on Route 2(west), approximately 1 mile west of the intersection with Interstate 495. A sign reading "1500 ft. rest area" alerts the driver to the rest area.

<u>Mileage</u>

0.00   Intersection of rest area exit road and Route 2.

        Proceed west on Route 2.

0.40   <u>Stop 1</u>: Curbing ends at the west end of the first large road cut. Pull over onto shoulder at this point. Here, the Tadmuck Brook Schist contains some siltstone intercalations which may show thickening and thinning and boudinage.

        The brown rust color seen on some joint surfaces and near the top and east end of the outcrop is brighter but more characteristic of the color seen in natural exposures.

        Some vein quartz is present both parallel and at an angle to the foliation.

        Continue west on Route 2

1.90   <u>Optional Stop</u>: Second rest area. Clinton Quartz Monzonite close to main trace(about 1000 feet to the east) of Clinton-Newbury fault. Narrow zones of shearing can be seen along the length of exposure.

        Proceed west on Route 2.

2.85   Take Routes 110-111 exit toward Ayer(north).

3.35   Turn right(east) from Route 110 onto Poor Farm road.

3.80   Many of the stones in these walls are examples of the poorly exposed coarse non-porphyritic subfacies of the Clinton Quartz Monzonite.

4.65   Turn left(north) onto Littleton road.

5.10   <u>Stop 2</u>: Park on the shoulder just north of the dip in the road beyond the white barrier posts where the road starts up toward a turn.

        Walk into the low area just west of the white barrier posts. Large natural exposures can be found on both sides of this low area. This series of outcrops is an almost complete section across a narrow portion of the Clinton-

Newbury fault zone. This cataclastic rock suite
(see text) contains some finely laminated mylonite gneiss
(hartschiefer) which could easily be mistaken for a
finely layered sedimentary rock.

Reverse direction and head south on Littleton road.

7.1   Road ends at intersection with Route 110, turn right
        (north) toward Ayer.

7.35   Optional Stop: Outcrop along Route 110.
        A plutonic rock probably consanguineous with one of the
        units of the Ayer crystalline complex. It is cut by
        numerous shear zones containing protomylonite(?).

        Continue north on Route 110.

7.75   Road goes into hallow bounded by white sheet metal
        deflection barriers. About 50 feet beyond the end
        of the barriers as the road starts up hill, turn
        sharply left onto an abandoned road and park. (Care-
        ful of traffic coming over hill when turning!)

        Stop 3: Walk north along the road to outcrop.
        This plutonic rock, probably part of the Ayer
        crystalline complex,   borders the Harvard Con-
        glomerate on the east. Narrow shear zones cut this
        outcrop.
        Walk back to old road. Proceed down old road until
        approximately opposite the barriers on the main road.
        On a bearing of N40-45W proceed to base of closest steep
        face of Pin Hill. Along the base of this slope is the
        sharp contact between the Harvard Conglomerate and a
        cataclastic rock.
        The conglomerate can be seen to good advantage up the
        slope from the contact. Look on the underside of pro-
        truding outcrops and boulders. Distinct tectonic stretch-
        ing of the pebbles is common.
        Moving northeast along the contact some concentrations
        of hydrothermal quartz can be seen. This contact can be
        followed around the hill to the northeast side.

        Return to car and proceed south back along Route 110.

8.05   Turn right(west) onto Harvard Depot road.

8.30   Stop 4: In roadcut at high point in road opposite
        Tensitron sign.
        The two faults bounding the Harvard Conglomerate at
        Pin Hill can be seen here but not to best advantage.
        Notice that on the west side of the exposure, the meta-
        sediments rapidly give way to a relatively homogeneous
        green-grey schistose rock with small red patches and
        small knots of grey, glassy quartz. Megascopic examination

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will reveal that this material is similar to the cata-
clastic rock at stop 3. Microscopic examination clearly
establishes the cataclastic origin of this rock.

Return to car. Continue along Harvard Depot road.

8.50   Intersection of Mill road. Continue straight ahead.
Outcrop on NW corner shows the porphyritic phase of
the Clinton Quartz Monzonite.

8.70   Bear right onto Craggs road.

9.07   Intersection of old Shirley road. Turn right(north)

9.25   Stop 5: A typical exposure of the dominant porphyritic
subfacies of the Clinton Quartz Monzonite. This location
is near the narrow transitional boundary with the non-
porphyritic subfacies.

Proceed north along old Shirley road.

9.50   Stop 6: Outcrop of the non-porphyritic subfacies of the
Clinton Quartz Monzonite.

Continue along old Shirley road.

10.00   Old Shirley road ends at the intersection with Route 110.
Turn left(north)

12.30   Entering rotary. Exit rotary along Route 2A(west) toward
Ayer. Immediately upon leaving rotary, turn right into
driveway marked by "Cains" sign.
Follow driveway around through parking lot toward the
back of the building. At road intersection just before
railroad tracks, turn right onto road paralleling the
railroad tracks.

12.67   Stop 7: A small outcrop in the clearing to the right
of the road.
This quartzite outcrop appears to show rhythmic sedimenta-
tion and possible penecontemporaneous deformation. This
unit is one possible source for the clasts seen in the
Harvard Conglomerate. (No hammers please)
Question: which way toward tops?

12.78   Continue along this service road to intersection, turn
right and return to rotary. Exit rotary as before but
proceed along Route 2A(west) past Cains property.

Continue over railroad bridge into Ayer Center.

13.88   Turn right(north) onto Washington St. Street marked
by large "H"(hospital) sign.

13.92   Turn right onto Newton St. Park in municipal parking lot.

Stop 8: Large outcrop(No Hammers) on the southeast side
of lot. This is an outcrop of the "porphyroblastic" sub-
facies of the Devens-Long Pond gneiss. Notice the shear
zone cutting the outcrop and the thickening and thinning
of the feldspathic veins.
The simplest explanation for the origin of this material
and its mesoscopic texture would be intrusion under syn-
tectonic conditions. However, some evidence(Gore, 1976)
exists to support the hypothesis that this material may
be the result of K-feldspathization and blastisis of a
possible volcanic sequence.

Drive to the end of the street. Turn right onto Columbia
St. and then turn left onto Central St.

14.22   Optional Stop: Large road cut in the "porphyroblastic"
subfacies of the Devens-Long Pond Gneiss.

14.40   Turn left(north) at intersection onto Harvard-Groton
road.

14.90   Stop 9: Road cut on west side of road.
"Porphyroblastic" subfacies of the Devens-Long Pond
Gneiss cut by pegmatities and dikes of fine Chelmsford
Granite. Thin section examination will reveal myrmekite
rims around most of the K-feldspar from this location.

14.98   Optional Stop: Devens-Long Pond Geniss cut by coarse
pegmatitic phase of the Chelmsford Granite.

15.20   Stop 10: Contact phase of the Chelmsford Granite.
Abundance of pegmatoid bodies a common feature of
Chelmsford Granite contacts.

15.40   Stop 11: Under transmission lines.
Ledges on hill on the north side of the transmission
line clearing are typical Chelmsford Granite.

Reverse direction and return to Central St.

16.40   Turn left(east) onto Central St.

18.25   Bear left at fork following Westford road sign.

19.25   Turn left(West) onto dirt road at sign "SRC"- Shanklin
Research Corp. Park at the back of parking lot or if in
rugged vehicle drive west on dirt road.
Stop 12: Along southwest side of Rocky Hill.
Different varieties of the Devens-Long Pond Gneiss can
be examined in the ledges north of the road. Pegmatites
and Chelmsford Granite cut the Devens-Long Pond Gneiss.

Be sure to go at least as far as the large smooth steep outcrop that runs in an almost continuous ramp from the top of the slope down to the bottom.

To return to Route 495, continue north on Westford road.

20.00 Turn right(east) onto Route 119 and continue until reaching Interstate Route 495.

Trip F-4

GEOLOGIC SETTING OF THE HARVARD CONGLOMERATE, HARVARD, MASSACHUSETTS

by

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"In Harvard and Bolton, east of the granite range and closely connected with the slates just described, beds of conglomerate occur, interstratified with argillite, which here coincides in strike and dip with the mica slates. (Strike, N.65° to 70°E. Dip, 45° to 80° N.W.) This conglomerate is very interesting from its relations to the surrounding rocks, and the remarkable changes that portions of it have undergone. It appears in a range extending from Pin Hill, in Harvard, to the summit of Wattoquotoc in the south-west part of Bolton, forming several high hills that are marked features of the landscape. The series of specimens that I have placed in the Cabinet of the Society shows that the pebbles have, in many cases, been flattened, bent, and even drawn out into layers, giving an agate-like structure to some of the rock. ..... The principal conglomerate beds lie between hills of porphyritic granite on the west and north, and mica slate and gneiss on the south-east, yet <u>not</u> a pebble of <u>granite</u> or <u>gneiss</u>, so far as I have seen, enters into its composition, and the slaty pebbles that occur, appear to belong to argillite rather than mica slate. Some ten miles to the south-west, however, are extensive beds of slate, interstratified with a quartzite closely resembling the pebbles that form the mass of the conglomerate. ...."

"The rock which immediately encloses the beds of slate and conglomerate at Harvard is of a very peculiar character, as shown by specimens that I have placed in the Society's Collection. It appears in unstratified masses, resembling granite, but mixed with fragments of slate, and destitute of mica; and also as a schistose feldspathic gneiss in which slaty particles take the place of mica; while the feldspar is in perfect rounded crystals, giving a porphyritic aspect to the rock." - L. S. Burbank, 1876a, pp. 45-46.

Pin Hill in Harvard, Massachusetts, in the southern part of Ayer 7 1/2 minute topographic quadrangle, is a resistant northeast trending strike ridge held up by interbedded polymict conglomerate and phyllite of the Harvard Conglomerate, first so designated a century ago by L. S. Burbank (1876, 1876a; also see Crosby, 1876, and Emerson, 1917). Northwest of the conglomerate there is a large outcrop area of Ayer Granite, and the contact is well exposed in a cut on the northeast side of Depot Street. In outcrops 700 feet northwest of the contact the granite is the typical porphyritic variety of Ayer Granite with carlsbad-twinned potassic feldspar megacrysts up to about 6 cm long, thus closely resembling some varieties of the Kinsman Quartz Monzonite of the New Hampshire Magma Series in New Hampshire (Billings, 1956). Conspicuous in the slightly altered matrix are slightly bluish quartz grains about 1 cm across, and small flakes of biotite. In outcrops twenty feet west

of the contact the feldspar is sericitized and fragmented, and large megacrysts are inconspicuous. In thin section quartz and feldspar show abundant strain effects and the matrix consists of fine mortar texture quartz and feldspar with abundant sericite and subsidiary chlorite. Feldspar becomes increasingly scarce closer to the contact and, within one or two feet of it, the "granite" consists essentially of quartz and white mica. The conglomerate immediately east of the contact contains quartzite cobbles up to 15 cm in largest dimension.

Hansen (1956) regarded the Ayer Granite as younger than the Harvard Conglomerate and intrusive into it, but commented on the absence of obvious contact metamorphic effects. The development of chloritoid in the matrix of the conglomerate and in the interbedded phyllites was attributed by him to metasomatism related to the origin of the "Unnamed Gneiss at Bare Hill Pond", bordering the Harvard Conglomerate on the east.

On numerous Harvard University field trips in the late 1950's and early 60's Thompson became convinced that the contact relations might be explained by an unconformity, with chemical weathering of the granite before deposition of the conglomerate, amd recrystallization, shearing, and hydration of the granite during the metamorphism and folding of the conglomerate,

On a field trip in the spring of 1964, Robinson and some students from the University of Massachusetts decided on the spur of the moment to seek further evidence for or against the unconformity hypothesis by tracing the contact northeast from the road cut along the northwest slope of the hill. The result was the discovery of the small exposure illustrated in Figure 1, about 500 feet northeast of the road cut. Figure 1 is a drawing from a photograph and the view is of a vertical surface that faces southwest.

The contact (Fig. 1) is a clear-cut unconformity. The aplitic dikes in the granite (now quartz-sericite schist) are truncated by the base of the Harvard Conglomerate and there appear to be clasts of the aplitic material in the conglomerate. The weathered granite was apparently less resistant to erosion than the aplitic rock so that the dike stood out as a ridge on the erosion surface. The absence of granite clasts also testifies to the weathered character of the granite. During subsequent deformation a strong, probably axial-plane, foliation was superimposed on the conglomerate and granite, and the dikes were apparently rotated into parallelism with the foliation if they were not already in that orientation.

Interbedded with the conglomerate and overlying it are gray, green and faintly purple phyllites. The phyllites and the matrix of the conglomerate contain quartz, chloritoid (abundant), near isotropic chlorite and white mica. Peter Bell (personal communication, early 1960's) reported the presence of paragonite and pyrophyllite in addition to muscovite in some specimens. X-ray diffraction study by E.A. Perry, Jr. (personal communication, 1976) of one specimen each of phyllite and of conglomerate showed only muscovite and, in addition, minor albite. The purplish layers and conglomerates contain finely divided hematite. The gray layers may contain carbonaceous material. The mineral assemblages in the phyllites and conglomerate matrix are characteristic of the low-grade regional metamorphism of a highly aluminous pelite and require no special metasomatic effects. Emerson (1917) suggested that the Harvard Conglomerate might be a tillite, but the

FIGURE 1.

highly aluminous nature of the matrix and the phyllites is difficult to explain in this interpretation. To us the preserved sedimentological features are characteristic of many basal conglomerates in New England (such as parts of the Clough Quartzite) and elsewhere.

The deformation history of the conglomerate itself is best illustrated in a small exposure at the high point of Depot Street (north side). Here the conglomerate pebbles show severe flattening and elongation in the plane of an early foliation. This pebble foliation and lineation was then deformed by tight folds overturned to the east, with development of a prominent west-dipping axial plane foliation. Some thin sections of the phyllite show a fine early mica foliation cut, in some cases at right angles, by a strongly developed slip cleavage. At the unconformity illustrated in Figure 1 the predominant foliation and the only one shown in the Figure is the early one. However, in the right lighting a slip cleavage may also be discerned that dips 10-15° more steeply.

The eastern contact of the Harvard Conglomerate sequence is exposed on the south side of Depot Street at the east end of the cut, and appears to be a post-metamorphic fault, perhaps Permian or even Triassic in age (see Castle et al., 1975 for a general discussion of faulting in this part of Massachusetts). The rocks east of this fault are part of the "Unnamed Gneiss at Bare Hill Pond" of Hansen (1956), and were regarded by him as of largely metasomatic origin (the "Green Eyrie Migmatite", see also Currier and Jahns, 1952). Castle et al.(1975), on the other hand, regarded these rocks as mylonitized Ayer Granite. To us some exposures of these gneisses, and of the rocks that border them on the east, the Vaughan Hills Member of the Worcester Formation of Hansen (1956), closely resemble rocks that are demonstrably metamorphosed volcanics elsewhere. This matter clearly needs further study.

We regard the Harvard Conglomerate and its associated phyllites as correlative with the basal units of the fossiliferous Pennsylvanian rocks exposed in the Worcester area (Perry and Emerson, 1903; Grew et al., 1970; Grew, 1973; also Grew, this Guidebook). Radiometric dating of the Ayer Granite (Zartman et al., 1965 and 1970; also more recent unpublished data of Zartman as summarized by Grew, this Guidebook) indicate that it is pre-Pennsylvanian, possibly as old as Ordovician.

Road Log

Starting point is the village green in center of Harvard, Massachusetts. We will assemble at the northeast corner of the triangular green a few yards east of and within sight of State Highway 111 at 1:30 P. M. on Friday. (This and Stops 1 and 2 are near the south edge of the Ayer 7 1/2 minute quadrangle. Stop 3 is in the Shirley 7 1/2 minute quadrangle).

Mileage

0.00   Proceed north on Route 111, passing exposures of "Unnamed Gneiss at Bare Hill Pond" (Hansen, 1956).

0.40   Turn left (N.W.) on Depot Street.

0.60   Stop 1: Pin Hill, for description see accompanying text.

0.60   Continue on Depot Street.

0.80   Stop 2: Ayer Granite, porphyritic phase. Turn right (N) on
         Mill Road, and park.
         Alternate Stop 2A, weather and time permitting. Continue 0.70
         mile northwest on Depot Street, then 1.1 mile southwest on Prospect
         Hill Road to highest point of road. Cut on left (E); Ayer Granite
         with primary feldspar foliation cut by aplite dikes. Panoramic
         view of Nashua Valley to west dominated by Mt. Wachusett (2006'),
         the highest peak in Massachusetts east of the Connecticut River.
         Mt. Wachusett lies at the west margin of the Fitchburg Granite
         pluton that marks the east edge of the broad central Massachusetts
         sillimanite zone of Acadian metamorphism. A narrow andalusite-
         sillimanite transition zone lies along the east margin of the
         pluton (Nelson, 1973), and the rocks exposed in the nearer lowlands
         are in the staurolite ($\pm$ andalusite), garnet, and chlorite zones.
         Farther away to the northwest are Mt. Monadnock and the Wapack
         Range in New Hampshire held up by well bedded sillimanite schists
         of the Lower Devonian Littleton Formation. Return to Stop 2.

0.80   Proceed north and northeast on Mill Road.

1.45   Turn left (N) on Route 111.

2.10   Turn right (E) on ramp for Route 2, westbound.

2.25   Proceed west on Route 2, passing outcrops on both sides of
         Ayer Granite.

5.15   Cross Nashoba River and pass entrance to Fort Devens. Exposure on
         right (N) of highly folded ankerite-bearing schists of Unit 2 of
         Peck (in press)(Oakdale Formation).

6.00   Stop 3: Large outcrop on right of interbedded dark gray chlorite
         phyllite and sandstone. Excellent cleavage-bedding relationships
         in large fold with second generation crenulations in axial plane
         cleavage. Primary stratigraphic tops shown by cross-bedding in
         sandy layers, also by graded bedding. Phyllites and sandstones
         like these contain large chiastolites a few miles to the southwest.
         These rocks are believed to be older than the Ayer Granite. They
         are assigned by J. H. Peck (in press) to his Unit 3 in the adjacent
         Clinton Quadrangle. Unit 3 overlies Unit 2 (Oakdale Formation of
         Emerson) that may be tentatively correlated along strike with
         Silurian rocks in Maine. The rocks exposed at Stop 3 bear consider-
         able similarity to parts of the Lower Devonian Littleton and
         Seeboomook Formations of western New Hampshire and Maine respect-
         ively. Some of the late structural features at Stop 3, as well as
         extensive retrograding of andalusite and staurolite in rocks to the
         southwest, may have been contemporaneous with deformational and
         metamorphic features observed at Stop 1.
         End of trip.

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Trip B-13

STRATIGRAPHY OF THE WEBSTER-WORCESTER REGION, MASSACHUSETTS

by

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Introduction: Many of the major structural-stratigraphic blocks of eastern Massachusetts are juxtaposed between Worcester and northeastern Connecticut (fig. 1), where stratigraphic units characteristic of these blocks can be seen in a relatively small area. The stratigraphy (fig. 2) from oldest to youngest consists of the Plainfield Formation in the north end of the Rhode Island massif; the Marlboro and Nashoba Formations and the Tadmuck Brook Schist of the Clinton-Newbury-Bloody Bluff thrust block; quartzite, metasilt-stone-phyllite, and the Eliot Formation in a fault sliver representing the southernmost extension of Merrimack Group rocks from the Clinton area; the Oakdale Formation of the Worcester lowland and the "Paxton Group" and Bigelow Brook Formation in thrust blocks to the west (fig. 1).

Stratigraphy:

Plainfield Formation (Precambrian?)

Lundgren (1962) named the Plainfield Formation from exposures in eastern Connecticut. It consists of medium-grained quartzite interbedded with fine- to medium-grained biotite-muscovite schist. The quartzite is light gray to buff in medium to thick beds where it forms almost all the section, and medium gray with greenish and purplish casts in thin beds where it is interbedded with pelitic schists. In both places it weathers slightly lighter. The West-boro Quartzite, a probable correlative to part of the Plainfield Formation is intruded by rocks dated as Precambrian (Nelson, 1975). The lower contact is an intrusive one, and the upper contact is faulted.

Marlboro Formation (pre-Silurian)

Bedded to massive amphibolite forms the upper part of the Marlboro Formation (Emerson, 1917); Bell and Alvord, in press) in the report area. This amphibolite is generally medium to coarse grained and dark gray to nearly black; it weathers slightly lighter and contains a few beds of quartzose-feldspathic gneiss. The basal contact is faulted, and the upper contact with the Nashoba Formation is gradational, although it may be locally faulted. The Marlboro is correlative in Connecticut with the Quinebaug Formation of Dixon (1964). The Marlboro and the overlying Nashoba Formation and Tadmuck Brook Schist are considered pre-Middle Ordovician in age by Alvord, (1975) on the basis of radioactive-age dating.

Figure 1. Structural-stratigraphic blocks of the Worcester-Webster region,
           Massachusetts

Explanation: Heavy lines, faults, dashed where approximately located; fine
lines, contacts; R.I., Rhode Island massif containing the Plainfield Formation;
M-N, block containing Marlboro and Nashoba Formations and the Tadmuck Brook
Schist; E, fault slivers of Eliot Formation and quartzite and metasiltstone-
phyllite units; O, block and area of Oakdale Formation; P, block containing
"Paxton Group"; B, block containing Brimfield Group. Intrusive rocks are not
shown. Numbers denote locations of stops in the road log. Compiled from
Barosh, 1974, and unpublished data by P.J. Barosh and G.E. Moore
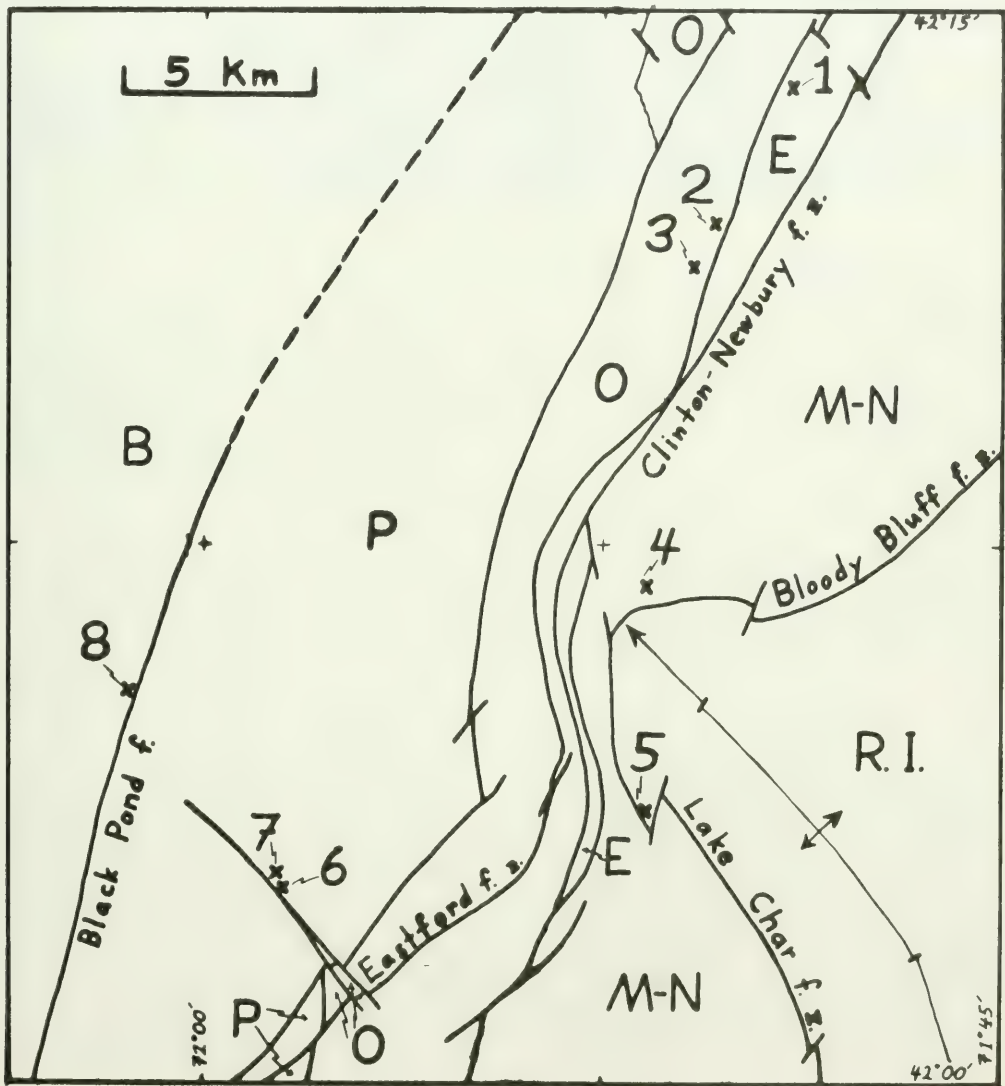
lower Paleozoic	Brimfield Group	Bigelow Brook Formation	fault
	"Paxton Group"	Southbridge Formation lower part	
Silurian(?)orDevonian(?)		Oakdale Formation	fault
Silurian		Eliot Formation	
Silurian(?)		Metasiltstone and phyllite Quartzite	fault
pre-Silurian(?)		Tadmuck Brook Schist	unconformity or fault
		Nashoba Formation	
		Marlboro Formation	fault
Precambrian(?)		Plainfield Formation	

Figure 2. Stratigraphic column for the Worcester-Webster region, Massachusetts

Nashoba Formation (pre-Silurian)

The Nashoba Formation of Hanson (1956) was redescribed by Bell and Alvord (in press), whose work is summarized in this volume by Alvord. The Nashoba is used here in its original broader sense, which includes the Shawsheen and Fish Brook Gneisses at the base. Briefly, this very thick unit is characterized by light- to medium-gray, medium- to coarse-grained, medium-bedded quartzose-feldspathic gneiss; beds of amphibolite and various types of schist and marble are common at certain horizons. The Nashoba is overlain by the Tadmuck Brook Schist at a slight angular discordance which probably represents an unconformity but could be due to faulting. The Nashoba correlates with the Tatnic Hill Formation of Connecticut.

Tadmuck Brook Schist (pre-Silurian)

The Tadmuck Brook Schist of Bell and Alvord (in press) is only known, in this area from one exposure in the Worcester South quadrangle. It is composed of rusty weathering, silvery, medium- to dark-gray sillimanite biotite-quartz muscovite schist to quartz-chlorite-biotite-sericite phyllite. It is generally highly sheared, and its upper contact is faulted.

Quartzite (Silurian?)

A thin quartzite exposed at one locality in the Worcester South quadrangle apparently correlates with the quartzite Peck (1975) referred to as Unit 1 in the Clinton area (Pec, in press). It is a light- to medium-gray, fine- to medium-grained, thin- to thick-bedded quartzite that weathers lighter gray. Its lower contact is faulted, and its upper contact appears conformable with the metasiltstone and phyllite unit.

Metasiltstone and phyllite (Silurian?)

A thin unit of greenish to purplish medium-gray thin-bedded metasiltstone in the Worcester South quadrangle is apparently correlative with that in the Clinton quadrangle (Peck, 1975) referred to as Unit 2 by Peck (in press). The upper contact is covered, but Peck has reported that Unit 2 underlies Unit 3, the overlying Eliot Formation.

Eliot Formation (Silurian)

The Eliot Formation is equivalent to the slate and phyllite, Unit 3, of Peck (1975, and in press), and probably also to Unit 4. It is a relatively uniform dark-gray sericite to muscovite phyllite to schist that is generally a well-bedded, thin-bedded unit with graded bedding it weathers to a lighter gray. It is commonly folded and is the only formation in the area to have a secondary foliation, not parallel to bedding, at several localities. The Eliot is correlated with the Silurian Eliot Formation of southern Maine (Hussey, 1962) on the basis of its distinct lithology and equivalent position in the stratigraphic sequence. Its upper contact is formed by a major fault in this area, but similar beds in the lowermost known Oakdale Formation to the west suggests that the Oakdale overlies it.

Peck (1975) considers the Eliot, along with the underlying Units 1 and 2, as Silurian or Devonian in age from a general correlation with formations to the north; Hussey (1962) correlated the Eliot and the two underlying units of southern Maine with Silurian rocks farther north in Maine.

Oakdale Formation (Silurian? or Devonian?)

The Oakdale Formation, originally the Oakdale Quartzite of Emerson (1917), consists of medium- to dark-gray or greenish-gray thin-bedded metasiltstone to phyllite which weathers light to medium gray or greenish or brownish gray. It is well laminated locally and has some graded beds near the exposed base. At least one unit within the formation contains partings and thin beds of muscovite schist. The contact with the overlying basal beds of the Paxton Group appears faulted in the Webster area, but in the southwest part of the Worcester North quadrangle and adjacent part of the Worcester South quadrangle it appears conformable (fig. 1). The Oakdale Formation is considered Silurian(?) or Devonian(?) in age as it probably stratigraphically overlies the Silurian Eliot Formation, as does the equivalent basal Berwick Formation in Maine.

"Paxton Group" (lower Paleozoic)

The Paxton Quartz Schist of Emerson (1917) has been divided into two formations by Moore (pers. comm.) which consist of medium-gray, thin- to medium-bedded, fine- to coarse-grained metagraywacke which weathers the same color or slightly darker with a brownish cast. The beds have a schistose to granulose structure and are composed mainly of quartz, biotite, and feldspar, which gives them a salt and pepper appearance. Calc-silicate-bearing beds occur at many horizons throughout the section. The upper part of the "Paxton" has been designated the Southbridge Formation informally by Moore (pers. comm.)(Pease, 1972), and the lower part is being redescribed as a new formation, which is equivalent to the Hebron Formation as mapped in the Eastford quadrangle (Pease, 1972). The lower part of the "Paxton" is fine grained and has generally thinner and more uniform beds than the Southbridge, which is medium to coarse grained and has fewer fine-grained beds. The contact between the two is gradational. The top of the Southbridge is bounded by the Black Pond fault.

Bigelow Brook Formation (lower Paleozoic)

The Bigelow Brook Formation forms the basal formation of the Brimfield Group (Peper, Pease and Seiders, 1975). Its lower gneiss member forms the westernmost and uppermost part of the stratigraphy discussed here. The lower gneiss member consists of light- to medium-gray, weathering lighter to rusty, medium- to coarse-grained quartz-biotite-feldspar gneiss interbedded with schist. Some gneiss is calc-silciate bearing, and sillimanite is common in the member. The Bigelow Brook Formation is considered to overlie the Southbridge Formation stratigraphically (Peper, Pease and Seiders, 1975).

Units at the top of the Brimfield Group are considered Devonian(?) by correlation with units to the north in New Hampshire; the Brimfield and "Paxton" Groups were designated Ordovician(?) to Lower Devonian by Peper, Pease and Seiders (1975). The correlation of Eliot with Silurian rocks probably restricts the age to Silurian(?) or Devonian(?).

(7½-minute quadrangle maps covered on this trip are the Leicester, Oxford (Stops 4 and 5), Southbridge (Stop 8), Webster (Stops 6 and 7) and Worcester South (Stops 1,2 and 3))

ROAD LOG

MILEAGE

0	Toll booth at Auburn Exit, interchange 10, of Massachusetts Turnpike. Oakdale Formation in roadcuts. (For description along Massachusetts Turnpike from Boston to interchange 10 see road log for "Faults and related deformation in the Clinton-Newbury-Bloody Bluff fault complex of eastern Massachusetts").
0.1	Veer left, entrance Rt. 12 north-290, Auburn-Worcester, and stay left following 290 East signs.
3.9	Worcester town line.
4.5	Right on exit 11, College Square, Worcester.
4.8	Right on College St. (becomes Pakachoag St. to south) Holy Cross College on the left.
5.2	Right on Kendig St. (a dirt street), go 100 m, and park on right. Walk west down road 40 m, turn left off road, and go about 60 m south to extensive outcrops around top of knoll--College Hill. STOP 1, Eliot Formation, medium to dark gray thin bedded. 0.5-to2-cm beds, metamudstone-phyllite with graded bedding. The formation appears to have formed as a distal turbidite sequence (Peck, in press). Sedimentary features very well shown. Overturned beds present.
5.3	Return to College St. and turn right.
5.5	Veer left.
7.3	Outcrops of Eliot on left 50 m north of powerline.
7.6	Low outcrops of Eliot on right and scattered outcrops next 0.2 mile on both sides of road.
7.9	Right just before overpass (Massachusetts Turnpike). Do not go under overpass.
8.1	Left onto Swanson Road. Pond on right is all that is left of Auburn Pond that extended to Massachusetts Turnpike. Shopping mall area created by leveling a drumlin at the present site of Sears and filling in the pond.

8.4   Left at signals onto Southbridge St.

8.6   Right 100 m beyond Gino's. Pull off pavement on right, near corner and park. Walk to low outcrops in gravel pit to north. STOP 2, Oakdale Formation, medium- to dark-gray metasiltstone and metamudstone, well bedded in 1- to 35-cm-thick beds. Graded bedding in the thinner more pelitic beds, laminations in the more quartzose slightly coarser grained beds. Sedimentary features are well shown for the Oakdale, which generally appears as a more uniform thin-bedded metasiltstone, but which has a deceptively massive-looking appearance in roadcuts, such as at the Auburn exit, and lacks obvious graded bedding. Refracted cleavage across the finer grained part of graded beds resembles cross-bedding. Many small folds and some pseudofolds (ptygmatic quartz veins). The thinner, finer grained graded-bedded layers, which are unusual in the Oakdale, may indicate that this lower part of the formation was formed in an environment transitional from that of the Eliot. Continue down side road.

8.8   Rejoin Southbridge St., turn right.

9.1   Pass under Massachusetts Turnpike.

9.4   Right on Water St. (just north of Auburn Elks), go 50 m, and park on right. Rock roadcuts on both sides. STOP 3, (extra stop if time permits). Oakdale Formation, medium- to dark-gray thin-bedded metasiltstone, few graded beds. Stop demonstrates the apparent differences between smoothed weathered outcrop and fresh blated roadcut exposures. The formation is as well bedded as at Stop 2, although it does not appear to be. Foliation parallels bedding. Outcrop is highly contorted and folded and has overturned beds in places. Many nonsystematic folds.

9.5   Left onto Oxford St., just beyond underpass beneath Rt. 290.

9.9   Right on Southbridge St., Rt. 12 South.

11.2   Right bend at signals at junction of Rts. 12 and 20, continue west. Driving over Oakdale Formation.

11.9   Left onto Rt. 12 south Oxford-Webster. Biotite quartz monzonite forms the hill to the left; the rigde to the right is composed of muscovite quartz monzonite, "Fitchburg granite."

12.4   Outcrop on right is silicic laminated Oakdale. A short distance ahead the intrusive rocks on either side merge, pinching out the Oakdale. The Oakdale reappears at the same position about a mile farther southwest.

13.5   Outcrops of quartz monzonite on both sides of valley.
              Intrusive rocks in this area tend to be relatively long
              and narrow. Some have intruded fault zones, as shown
              by disjunctions between rocks on either side of the
              intrusive rock and by xenoliths of mylonite. Some also
              have moved along contacts.

14.1   Clinton-Newbury fault zone traverses valley on left and
              crosses road.

14.5   Boulders on left of a variety of intrusive rocks from the
              fault zone; many are highly sheared to mylonitized. Out-
              crop of Nashoba Formation on left just beyond diner. Large
              Pleistocene river came down the valley and disgorged
              sediments into a lake here, building a large flat-topped
              delta to the south on which Oxford center is built.

16.5   Oxford Center left onto Sutton Ave. east; sign points to
              Rt. 52, Webster.

17.1   Cross over Rt. 52 and park on right just beyond entrance
              ramp to Rt. 52 North, Auburn-Worcester (present end of
              interstate and entrance unmarked). Carefully walk across
              road to outcrops along entrance ramp to Rt. 52 North from
              west lane Sutton St. STOP 4, Contact Marlboro Formation
              (Quinebaug Formation) with Nashoba Formation of Hanson
              (1956) (Tatnic Hill Formation). Well-bedded volcaniclas-
              tic sequence which has foliation paralleling bedding.
              Amphibolite at south end of cut, and also underlying the
              valley to south, forms the top of the Marlboro Formation,
              designated Quinebaug in Connecticut by Dixon (1964).
              The Marlboro is dark-gray layered amphibolite containing
              a few beds of quartzose-feldspathic gneiss. Much of
              the upper part of the formation has 0.5- to 10-cm thick
              beds, but beds 1 m or so thick are not uncommon. This
              bedded amphibolite correlates with the Sandy Pond Amphibo-
              lite Member of the Marlboro of Bell and Alvord (in
              press). To the north is the light- to medium-gray,
              medium-bedded quartzose-feldspathic gneiss that forms
              the most common lithology in the Nashoba Formation,
              designated Tatnic Hill Formation in Connecticut (Dixon,
              1964). This gneiss is probably equivalent to the Shaw-
              sheen Gneiss of Bell and Alvord (in press) and Alvord,
              (this volume). Note the high metamorphic grade here in
              contrast to that at the previous stops. The few large
              garnets found in the gneiss here are unusual. Minor
              faulting occurs at the contact, and either the contact is
              repeated or a bed of amphibolite occurs near the base of
              the gneiss. The rocks here are highly sheared and faulted
              as they are just above a major regional thrust that under-
              lies the valley to the south. Light-gray pegmatite, both
              foliated and nonfoliated, is present along many of the
              shears and thrust faults.

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Back up carefully and enter entrance ramp Rt. 52
North. Pass under Sutton Avenue and turn right onto
Exit 4 West Sutton Avenue, Oxford, and pass outcrops
of STOP 4. Enter Sutton Avenue west, cross over Rt.
52, and turn right into entrance to Rt. 52 South,
Webster - Thompson Ct.

18.4   Pass under Sutton Avenue a second time. You should now
        be heading south on Rt. 52. Valley underlain by amphibolite
        of Marlboro Formation.

18.8   Crossing major north-dipping thrust fault which separates
        the structural block containing the Marlboro and Nashoba
        rocks on the northwest from those of Rhode Island massif
        to the south. South of the fault is a broad northwest-
        plunging anticline rimmed by quartzite of the Plainfield
        Formation intruded by syntectonic intrusive gneiss,
        approximately quartz monzonite in composition.

19.4   Crossing anticlinal axis.

19.5   Intrusive gneiss crops out on both sides of roadway, the
        intruded quartzite beds capping the outcrop on the left.
        More quartzite is present along northbound lanes. The
        intrusive rock is moderately to strongly foliated, the
        feldspars being generally rounded rather than sheared
        and fractured. The rock has generally undergone altera-
        tion, which has produced pink feldspar and has chloritized
        the mafic minerals. Faults cut the rock here; several
        nearly parallel the road, dipping steeply to the west,
        and a few are approximately perpendicular to the road.

19.8   Pass under Holbrook Street.

21.3 - 22.1   Outcrops of Plainfield Formation along the road.

22.2   Right on exit 2, Rt. 16, Webster-Douglas, drive through
        cut in Plainfield Formation.

22.5   Right on Rt. 16 west, go about 50 m and turn left into
        parking lot (at north shore of Lake Webster) and park.
        Walk back to the roadcut just driven through. STOP 5,
        Plainfield Formation; greenish to purplish medium-gray
        thin-bedded interbedded dirty quartzite and schistose
        pelitic beds. Beds range from 0.5 to 30 cm in thickness
        but are mostly 2 to 5 cm thick. Foliation parallels
        bedding. The beds are crinkled to contorted, which is
        typical in this region of units of alternating beds of
        different competence. Overlying beds to west become more
        quartzitic and massive, forming light-gray to buff thin-
        to medium-bedded quartzite. Beds at west edge of outcrop,
        next to the fire plug, are broken up; a major fault lies
        a short distance to the west, separating the Plainfield
        from the Marlboro-Nashoba rocks. Left from parking lot,
        continue west.

22.7   Intersection Rt. 16 and Rt. 12. (Lunch stop, left, south, on Rt. 16, 0.4 miles farther, turn left on New Beach Dr. and pass under Rt. 52 for Webster Memorial Beach at end of peninsula for lunch stop. Peninsula is part of a head of glacial outwash. Several ice stands are recorded in the lake by paired peninsulas. Return to Rt. 16 and Rt. 12 intersection and turn left, west, onto East Main Street, Route 12. Add 1.6 miles to mileage for this loop.) Driving over Nashoba Formation.

23.6   Veer left at signal. The boulders on the left are composed of Eliot Formation and porphyritic quartz monzonite. Driving over southern end of fault sliver of Eliot, which underlies Webster center.

23.9   Right at signals, Webster center.

24.3   Dudley town line. Driving over intrusive complex of quartz monzonite.

24.7   Continue straight, west, on West Main Street, Rt. 197, next outcrop on left muscovite quartz monzonite.

25.7   Veer left at road split.

27.4   Crossing Center Road. Entered onto Oakdale formation near top of hill to east. Weathered Oakdale in bank on southeast corner. Muscovitic part of Oakdale here. Muscovitic schist partings to 2-cm-thick beds between greenish medium-gray laminated silicic metasiltstone in 2- to 8-cm-thick beds. This unit is rarely exposed but appears to be widespread.

27.8   Thompson town line, Connecticut border.

28.1   Quinebaug, right on Rt. 131 North. Driving up Quinebaug River valley, which follows a northwest-trending fault zone (fig. 1).

28.4   Dudley town line, Massachusetts border.

28.7   Quinebaug River crossing. Entering onto the lower part of the "Paxton Group," a thin- to medium-bedded meta-graywacke.

30.4   Outcrop in creek 20 m west of road junction is part of a gradational sequence between the lower part of the "Paxton" and the Southbridge Formation.

30.6   Right at West Dudley, drive between factory buildings, cross bridge and up gravel terraces.

31.0   Right at north end of bridge over flooded railroad cut.

31.1   Veer right onto dirt road, watch out for gravel trucks, travel 0.2 mile and turn around in entrance to overgrown road on left, return 0.1 mile and pull off to right side of road at the spring (year-around flow of cold water). STOP 6, Gradational sequence between the lower part of the "Paxton Group" to the east and the overlying South-bridge Formation to the west. Medium-gray thin- to medium-bedded metagraywacke. The rocks are slightly to moderately foliated parallel to bedding and vary between a schistose and granulose structure. The bedding in cuts appears thicker than it is, as weathering of many of the thicker appearing beds commonly reveals that they are composed of two or more beds. The fine-grained beds at the east end of the outcrop are typical of the lower part. Towards the west end, medium- to coarse-grained beds more typical of the Southbridge appear. The pegmatite seen here commonly occurs in both formations.

31.5   Return to split in road and make a sharp right turn, continue 0.1 mile to curve in paved road and pull off to left onto dirt road under powerlines, and park. Walk north about 60 m to good exposure of bluff northwest of road. STOP 7, Southbridge Formation. Typical Southbridge outcrop, coarser grained, slightly thicker, and more irregular beds than at the last stop.

32.3   Return to Rt. 131 and turn right, extensive exposures of Southbridge along an old railroad cut that follows north-east side of river.

32.7   Southbridge town line.

34.4   Passing bridge on right. Good exposures of Southbridge at bluff at other side of the bridge. The beds here are slightly finer grained and thinner bedded than ususal in the Southbridge and are more like those at STOP 6.

35.5   Outcrops of Southbridge.

35.6   Stay right passing traffic circle, and cross the Quinebaug River.

36.2   Veer right onto Worcester Street. Road traverses west side of a valley controlled by the Black Pond fault, which separates the Southbridge on the east from the Bigelow Brook Formation on the west. Scattered outcrops of Beigelow Brook along ridge to left.

36.9   Park on right and walk across the street to the
outcrops on the north side of the Central Retreading,
Inc., building. STOP 8, Bigelow Brook Formation,
lower gneiss member. Medium-gray thin- to medium-bedded
quartzose feldspathic gneiss interbedded with thin-bedded
darker schist. Some gneiss units contain calc-silicate
minerals and may have a slight greenish cast. Relict
graded bedding is present locally. The Bigelow Brook
units are distinctly coarser grained and have more
schistose beds than those of the Southbridge Formation.
The foliation parallels the bedding. The metamorphic
grade increases westward from Dudley; this outcrop is
very close to the sillimanite-orthoclase isograd. Some
shearing, related to the fault to the east, is present.
Continue northward, except those going towards south-
eastern Connecticut or Rhode Island, who should return
to Southbridge and go east on Rt. 131.

37.7   Charlton town line.

41.0   Rt. 20, end of guide. Left for those going west or south;
6 miles to Sturbridge for Rt. 15 south or Massachusetts
Turnpike west. Right for those going towards Boston or
northeast; 10 miles to Auburn for Rt. 290 or Massachusetts
Turnpike east.

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Trip F-2

Lower Paleozoic Rocks West of the
Clinton-Newbury Fault Zone,
Worcester Area, Massachusetts.*

by

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Introduction

The stratified rocks of the easternmost part of the Merrimack
synclinorium, west of the Clinton-Newbury fault zone, will be the
main emphasis of this excursion. The field trip is designed to
coordinate with other N.E.I.G.C. excursions (this volume) in east-
central Massachusetts by Grew, Barosh, Pease and Fahey, and Stone.

The stratified rocks of the Worcester area occur in a complex
westerly dipping sequence. Type localities for many of Emerson's
(1917) classic units are found within the region. A low-grade
(chlorite zone) metamorphic trough passes through the Worcester
area (Thompson and Norton, 1968), with the grade of metamorphism
increasing both to the east and west away from the axis of the
trough. Just to the east of Worcester, the Clinton-Newbury fault,
an offset of regional significance (Skehan, 1968, 1969), separates
these rocks from the Nashoba and Marlboro Formations at high
metamorphic grade to the east (Bell and Alvord, 1974; see Pease
and Fahey, this volume).

Most of the rocks west of the Clinton-Newbury fault zone in
central Massachusetts are now believed to be of probable Silurian(?)
and (or) Devonian(?) age. Grew (1973; see Grew, this volume) has
shown that the Pennsylvanian exposures in the area are limited to
a few small remnants (Fig. 1). Emerson (1917) was thus probably
in error in assigning a Carboniferous age to most of the rocks in
the Worcester area.

The present work in the Worcester North quadrangle and surrounding
areas is part of a cooperative program by the U.S. Geological Survey
and the Massachusetts Department of Public Works. As this work is
still in progress by the author and several others, this report
must be considered to be of preliminary nature. Stratigraphic names
and correlations presented here have not been formally accepted by
the U.S. Geological Survey or even by all of my colleagues mapping
in adjacent areas. Stratigraphic correlations in unfossiliferous,
highly deformed metamorphic rocks are always most difficult and

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* Publication authorized by the Director, U.S. Geological Survey.

need to be solved by mapping on a regional scale; this mapping is not yet complete. Therefore, I have tried to present the stratigraphic names and designations in the literature for the individual units seen on the trip, as well as my own interpretations. Generally, the recently published stratigraphic succession from the Clinton quadrangle (Peck, 1975, 1976) has been followed here.

Previous Work

Although earlier descriptions of the geology of the Worcester area are available (the Pennsylvanian coal mine in particular attracting much attention), Perry and Emerson (1903) compiled the first detailed bedrock geologic map of the area with comprehensive descriptions of the units. Emerson (1917) included much of this work, with revisions, in his classic statewide compilation and designated type-localities of several formations in the general Worcester area. More recent studies have been completed on the plant fossils at the Worcester coal mine (Grew, Mamay, and Barghoorn, 1970) and the geology of the Pennsylvanian and surrounding rocks (Grew, 1970, 1973). Peck (1975, 1976) has recently mapped the Clinton quadrangle and established a stratigraphic succession there. The Webster quadrangle to the south has recently been mapped by Barosh (1974). Detailed studies in the Wachusett-Marlborough tunnel to the northeast have been made by Skehan (1968), Skehan and Abu-moustafa (1976), and Abu-moustafa and Skehan, (1976). Bell and Alvord (1974, 1976) have compiled the first regional comprehensive studies of the rocks east of the Clinton-Newbury fault zone (see Pease and Fahey, this volume).

Stratigraphy

Nashoba Formation: The Nashoba Formation consists of gray to black, layered biotite gneiss, biotite schist, feldspathic gneiss with common megacrysts of feldspar, and minor augen gneiss. Garnet and sillimanite porphyroblasts are locally present, as are calc-silicate granulite and amphibolite layers. The Nashoba was named by Hanson (1956) for exposures along Nashoba Brook in the Maynard and Westford quadrangles. Previously, these rocks in the Worcester area had been called the Bolton Gneiss by Perry and Emerson (1903) and "gneisses and schists of undeterminated age" by Emerson (1917).

"Science Park unit*": An informally named unit well exposed at the Worcester Science Park, which includes gray, moderately foliated, medium-grained quartz-feldspar-biotite gneiss or schistose gneiss with garnet porphyroblasts and rare sillimanite. Very rusty-

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* Unpublished name used informally for convenience of discussion and reference.

weathering, dark gray, carbonaceous phyllite or schist is present locally. This schist contains a few coticule layers near the western boundary of the unit.

"Tower Hill Quartzite": The "Tower Hill Quartzite" is a distinctive light gray to buff, massive orthoquartzite with beds of dark gray phyllite or mica-schist prevalent near the contacts. Biotite and garnet porphyroblasts are common in the schist. Quartz-pebble conglomerate has been noted at one locality (STOP 3). The "Tower Hill Quartzite" was named by Grew (1970) and is equivalent to his Unit C (Grew, 1973) and to Peck's (1976) Unit 1. This unit was included in the Oakdale Quartzite by Emerson (1917).

Oakdale Quartzite: The Oakdale Quartzite includes green-gray to purplish-gray, impure quartzite, quartz-rich phyllite or meta-siltstone, with interbedded phyllite, mica-schist, and laminated quartz-phyllite (quartz-rich laminae 1 cm. thick or less, separated by even thinner micaceous partings). Ankerite and (or) calc-silicates are common accessory minerals. Local lenses of black to gray phyllite and carbonaceous phyllite are present. The Oakdale Quartzite was named by Emerson (1917) and corresponds to the Worcester Quartzite of Perry and Emerson (1903), Unit D of Grew (1973) and most probably Units 2 and 5 of Peck (1976).

Worcester Phyllite: The Worcester Phyllite consists of gray, well-foliated micaceous phyllite or schist with interbeds of impure quartzite or meta-siltstone a few centimetres to one metre thick. Grading is common in these beds, and many contain minor amounts of calc-silicate minerals (usually hornblende or actinolite). This unit has been interpreted as a meta-turbidite by Peck (1976), who indicates that the abundance and thicknesses of the meta-siltstone beds increase toward the west in the Clinton quadrangle. Also included in this formation are coticule-bearing, impure quartzite beds that were included within the Oakdale by Emerson (1917).

The Worcester Phyllite has many nomenclature problems associated with it, since both known Pennsylvanian (Grew, Mamay, and Barghoorn, 1970) and units now believed to be pre-Pennsylvanian have been included within it (Emerson, 1917; Perry and Emerson, 1903). I have chosen here to keep the name Worcester Phyllite for the wide-spread pre-Pennsylvanian rocks described above and to place the known Pennsylvanian deposits into another unit. The Worcester Phyllite so defined would then correlate approximately with Units B and E of Grew (1973) and Units 3 and 4 of Peck (1976). It would also include Emerson's (1917) Boylston Schist.

Pennsylvanian rocks: Rocks of known Pennsylvanian age (Grew, Mamay, and Barghoorn, 1970) at the Worcester coal mine locality include shiny gray to dark gray, carbonaceous phyllite with thin beds of impure meta-anthracite. Rocks of probable Pennsylvanian age (Grew, 1973) occur near the Worcester railroad yards adjacent to STOP 8 (Figure 1). They include brown-gray mudstone to phyllite and car-bonaceous phyllite with thin beds of feldspathic granule conglo-

merate, arkose, and rare stretched granite-pebble conglomerate (see Grew, this volume). These rocks were included in the Worcester Phyllite by Perry and Emerson (1903) and Emerson (1917), and in Units F and G of Grew (1973).

Igneous Rocks

The igneous rocks in the area include the following:

"Millstone Hill Granite", a white to light gray, medium-grained, largely unfoliated, blue quartz-bearing granite to quartz monzonite.

Fitchburg Granite, a two-mica, fine-to medium-grained, white to light gray, weakly foliated to unfoliated granite typical of the New Hampshire Plutonic Series (Billings, 1956).

Ayer Granite, a light gray, moderately coarse-grained, two mica granodiorite to granite that locally contains large feldspar phenocrysts.

Foliated granodiorite, a strongly foliated, medium-grained granodiorite in the southeastern part of the Worcester North quadrangle that contains numerous biotite-rich inclusions elongated parallel to the foliation.

Age and Correlation

The most recent summary of the age and correlation of the pre-Pennsylvanian rock units pertinent to the Worcester area is given by Peck (1976). Grew, Mamay, and Barghoorn (1970) summarize the fossil evidence for the Pennsylvanian age of the rocks at the Worcester coal mine. No fossils have been found in the pre-Pennsylvanian rocks in the region. A questionable Silurian age is established for the "Tower Hill" and Oakdale Quartzites by correlation with the Merrimack Group in southeastern New Hampshire (Billings, 1956) and York County, Maine (Hussey, 1968). The Merrimack Group is dated by correlation with the fossiliferous Silurian rocks near Waterville, Maine (Osberg, 1968). The Worcester Phyllite is considered Devonian(?) or Silurian(?) by tentative correlation with southeastern New Hampshire and southwestern Maine or by correlation with the Littleton Formation in south-central New Hampshire. The Nashoba is best dated as Ordovician(?) or older (see Pease and Fahey, this volume). The Ayer, Fitchburg, and "Millstone Hill" Granites are probably Devonian. Zartman and others (1965) have determined rubidium-strontium whole rock and muscovite ages of 345 ± 15 m.y. and 360 ± 10 m.y. for the "Millstone Hill Granite". The strongly foliated granodiorite in the southeastern part of the Worcester North quadrangle is thought to be pre-Acadian.

Figure 1
Simplified geologic map
eastern
Worcester North
quadrangle*

Igneous Rocks
  fg. Fitchburg Granite
  ag. Ayer Granite
  mg. "Millstone Hill Granite"
  fgd. foliated granodiorite

Pennsylvanian rocks

Worcester Phyllite

Oakdale Quartzite

"Tower Hill Quartzite"

"Science Park unit"
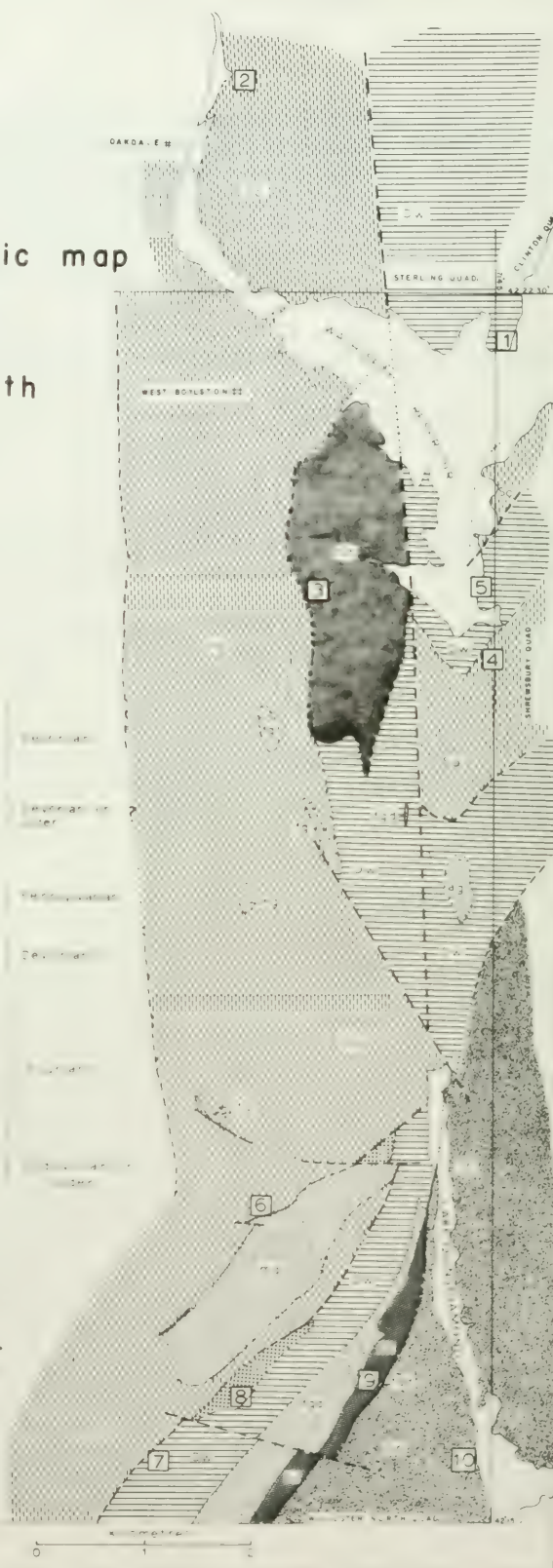
Nashoba Formation

Contact   Approximate   Inferred

Fault   Approximate   Inferred

Field trip stop ⑤

* Stratigraphic names and correlations presented here have
  not been formally accepted by the U. S. Geological Survey.

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LOWER PALEOZOIC ROCKS WEST OF THE CLINTON-NEWBURY
FAULT ZONE, WORCESTER AREA, MASSACHUSETTS

Road Log

The trip will include part of the Worcester North, Sterling, and Shrewsbury 7 1/2' quadrangles. Bring lunches.

Meet at the Lincoln Plaza Shopping Center across from Sheraton Lincoln Inn, on Route 70 north of Worcester, by Papa Gino's restaurant. To reach Lincoln Plaza, follow Rt. 70, 2.2 miles northeast from the traffic circle where Rts. 9, 70 and 122A junction, north of Worcester Center. If approaching Worcester by I290 from the east, exit directly onto Rt. 70 North at the Lincoln Street exit (not the exit marked "to 70 North", Plantation Street) and proceed 0.7 miles north on Rt. 70. The most convenient way for participants arriving by I290 from the south and west is for them to leave I290 at the exit for Rt. 9 East, turn left (west) at the top of the ramp and proceed two blocks to the above traffic circle.

Trip will leave Lincoln Plaza Shopping Center at 9:00 A.M. Early arrivals may examine outcrops of the Oakdale Quartzite opposite the shopping center along Rt. 70.

MILEAGE

Cum.	S/S	
0.0	0.0	Road log begins at exit from parking lot onto Rt. 70; TURN RIGHT (north).
0.1	0.1	Outcrop, Oakdale Quartzite on right.
0.3	0.2	Bear left and stay on Rt. 70. Good exposures of Oakdale Quartzite are along here.
0.7	0.4	Junction with Plantation St. at light; stay straight on Rt. 70, entering Shrewsbury.
2.2	1.5	Bear right and stay on Rt. 70. Oakdale Quartzite ahead on hill to left.
2.6	0.4	Enter Shrewbury quad.
3.4	0.8	Junction Rts. 70 and 140; TURN LEFT (north) onto Rt. 140.
3.6	0.2	Outcrops of Oakdale Quartzite. We will return to these later at Stop 4. Re-enter Worcester North quad.
4.1	0.5	Wachusett Reservoir on right.
4.5	0.4	Entering West Boylston.
4.9	0.4	Large forest beds in Pleistocene delta to left.
6.3	1.4	Junction Rts. 140 and 12; TURN RIGHT (northeast) onto Rts. 12 and 140.

6.8	0.5	Continue on Rts. 12 and 140; SHARP RIGHT under railroad overpass.
7.0	0.2	Cross Wachusett Reservoir.
7.2	0.2	Junction Rts. 140 and 12 on east side of reservoir; stay right on Rt. 12. Entering Sterling quad.
7.4	0.2	Junction Rts. 12 and 110; BEAR RIGHT (east) onto 110.
7.5	0.1	Note road to left, opposite the Dutch Cupboard gift shop. We will be returning here following Stop 1.
8.0	0.5	Pass under powerlines; outcrop of Oakdale on left.
8.9	0.9	Small outcrop of Worcester Phyllite on left.
9.0	0.1	TURN RIGHT (south) into driveway by house, opposite large red barn of Mt. View Farm. This is an access to M.D.C. property.
9.05	0.05	Pass through gate (usually locked, key may be obtained from superintendent at Wachusett Dam in Clinton).
9.1	0.05	Pass second gate.
9.2	0.1	Just beyond second gate TURN RIGHT and pass immediately through another gate. Follow this road to Wachusett Reservoir.
10.1	0.9	TURN LEFT at T junction. Enter Worcester North quad.
10.15	0.05	TURN RIGHT.
10.3	0.15	TURN RIGHT and follow to end of road.
10.5	0.2	Park at loop. Walk downhill to southeast, to outcrops along the shore on the east side of Shalon Point. Boundary of Shrewsbury and Worcester North quads. M.D.C. property; No Smoking and of course, No Littering.

STOP 1. Worcester Phyllite, Emerson (1917); Unit E, Grew (1973); Unit 3, Peck (1976). Rock is gray weathering, light gray, fine-grained, fissile phyllite with interbeds of meta-sandstone or siltstone a few cms. to 1/2 metre in thickness. The metamorphic grade here is low, biotite grade or less. Grading in some of the meta-sandstone beds indicates tops here are to the west, and the beds are right side up. Abundant minor folds make these outcrops an excellent place to illustrate fold measurement techniques to students. The folds generally plunge northeast at moderate angles with axial surfaces that strike north to northeast and dip steeply west. Some fold axes can be seen to porpoise (roll over) in the outcrop. The folds are generally asymmetrical and are dextral (Z)folds

when viewed down plunge to the northeast. They fold
bedding and also an earlier schistosity and lineation.
In the phyllitic beds, a cleavage is well developed
parallel to the axial planes of the folds.

Return to cars and retrace route to Rt. 110. Re-enter
Sterling quad.

12.0   1.5   TURN LEFT (west) onto Rt. 110.

13.5   1.5   SHARP TURN RIGHT (north) onto Prescott St., just
               before intersection of Rts. 110 and 12 (by Dutch
               Cupboard gift shop, large maroon sign).

13.6   0.1   Junction Rt. 12 and Prescott St. Continue across
               Rt. 12 on Prescott St.

14.9   1.3   At railroad crossing, park and walk west along
               railroad tracks about 150 metres to STOP 2.

STOP 2.   Outcrops of the Oakdale Quartzite near the type locality
          of Emerson (1917). Rock is gray-weathering, light gray
          to shiny gray phyllite and quartz-rich phyllite, inter-
          bedded with tan to gray-green weathering beds of impure
          quartzite and meta-siltstone a few cms. to 1 metre thick.
          These beds are slightly calcareous and commonly contain
          numerous brownish ankeritic spots. Thin laminae of gray-
          green micaceous phyllite are present in some of the meta-
          siltstone beds. This locality illustrates the variety
          of rock-types in the Oakdale Quartzite.

          Return to cars. Turn around and head south on Prescott
          Street.

14.95   0.05 TURN RIGHT almost immediately onto unmarked gravel
               road. This is Pleasant St.

15.95   1.0   Junction with Rt. 140; TURN RIGHT (north) onto 140,
               to village of Oakdale.

16.1   0.15 At west end of bridge. TURN LEFT onto Thomas St.
               and proceed south along the west side of Wachusett
               Reservoir.

16.4   0.3   Exposure of Pleistocene delta sands to right.

16.6   0.2   Enter Worcester North quad.

17.3   0.7   Continue straight at intersection.

17.8   0.5   Continue straight at intersection.

17.9   0.1   Pass West Boylston Post Office on right.

18.1   0.2   Junction with Rts. 12 and 140; continue straight on
               Rt. 140.

18.5   0.4   Junction with Worcester St. Stay left; continue on
               Rt. 140.

18.6	0.1	TURN RIGHT onto Maple St.
19.4	0.8	At Y intersection, take left fork onto Shrewsbury St. Outcrop of Oakdale on left.
19.7	0.2	Park along roadside or in pull-off on right. Walk along dirt road approximately N40E, 200 metres into the woods to outcrops.

STOP 3. "Tower Hill Quartzite" (Grew, 1970), Unit C of Grew (1973), Unit 1 of Peck (1976). The first knoll consists of dark gray to rusty-weathering mica schist and light gray ortho-quartzite. Porphyroblasts of garnet and biotite are common in the schist.

Proceed east 30 metres to south end of second small hill. Outcrops are gray quartzite with interbeds of quartz-rich mica schist and quartz pebble conglomerate. The conglo-merate has a quartz-rich schistose matrix. The pebbles are flattened in the foliation plane and elongated parallel to the prominent quartz-streaming lineation that plunges north at shallow angles.

Proceed north along the ridge about 75 metres to the out-crop with several large blown-down trees on it. This is the best exposure of the quartz-pebble conglomerate, which here has rounded quartzite and vein quartz pebbles to 10 cm. in length in a quartz-rich schistose matrix. These pebbles are not deformed. On top of the hill, the ortho-quartzite is well exposed and folded with fold axes parallel to the north-plunging lineation.

Return by heading south to old dirt road at the edge of the woods and follow it west to the cars. Continue south on Shrewsbury St.

20.1	0.4	Outcrops on left, behind oil tanks, are the "Tower Hill Quartzite".
20.6	0.5	Hospital Drive; TURN LEFT toward Worcester County Hospital.
21.0	0.4	Continue left at Y-intersection.
21.1	0.1	Stay straight.
21.8	0.7	Junction with Rt. 70; TURN LEFT onto Rt. 70.
22.2	0.4	Enter Shrewsbury quadrangle.
22.9	0.7	Junction of Rts. 70 and 140; TURN LEFT onto 140.
23.1	0.2	Enter Worcester North quadrangle. Pull off onto the right shoulder of the road and park.

STOP 4. Oakdale Quartzite. Typical light gray to purplish-brown weathering calcareous meta-siltstone and interbedded gray

to gray-green phyllite of the Oakdale Quartzite
(Emerson, 1917; Unit D, Grew, 1973; Unit 2 of Peck,
1976). Siltstone beds range in thickness from 1 to 10
cm. and are separated by thin partings of micaceous
phyllite or interlaminated with paper thin phyllite
partings on a scale of a few millimeters. Ankerite
causes the characteristic purplish-brown weathering
spots in the siltstones. The beds here strike N35°E
and dip 35°NW. Note the small, tight folds with axial
surfaces approximately parallel to the bedding. Late
kink bands with steeply dipping axial surfaces are
conspicuous.

Return to cars. Proceed on Rt. 70 to bottom of the hill.

23.5   0.4   Carefully turn around and retrace route to the
                 Junction of 140 and 70. Enter Shrewsbury quad.

24.1   0.6   Junction of Rt. 70 and 140; TURN LEFT (east) onto
                 Rt. 70 towards Clinton.

24.5   0.4   TURN LEFT onto West Temple St., proceed to end.
                 Turn around and park. Walk to west end of W. Temple
                 St., enter Worcester North quad. and follow path
                 north on east side of Wachusett Resevoir. M.D.C.
                 property. No Smoking please.

STOP 5.   Along the shore are excellent exposures of the Worcester
           Phyllite of Emerson (1917) (Unit E of Grew, 1973; Unit
           3 of Peck, 1976), at the staurolite grade of metamorphism.
           The rock is a dark-weathering, gray muscovite-quartz
           schist with porphyroblasts of biotite, garnet, and
           staurolite. Thin interbeds of impure quartzite and
           actinolite- or hornblende- bearing meta-siltstone to
           several cms. thick are common. Many of the porphyroblasts
           in the schist have been rimmed by retrograde chlorite.
           Conspicuous, tight, early, northwest-plunging folds can
           be seen here in the meta-siltstone beds when the lake
           level is low.

           Continue north along the lake in similar rocks for about
           0.5 kilometres, to the point where the path turns
           abruptly away from the lake at a rock cliff about 8
           metres high. STOP HERE, this is the furthest point of
           the walk. The rock at this point and in the outcrop 15
           metres to the south is an impure marble unit first
           noted by Grew (1970). The rock consists of interbedded
           impure, punky brown-weathering marble; more resistant,
           greenish-gray calc-silicate bearing granulites; and
           rusty-weathering, dark gray mica schist that contrasts
           with the non-rusty weathering schists previously examined.
           Two thin beds of nearly pure actinolite are present.
           Skarn-type reactions occur at the contact between some of
           the calcareous and schistose beds.

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Return to cars via path.

24.7	0.2	Proceed east on West Temple St. to Rt. 70; TURN RIGHT onto Rt. 70.
25.1	0.4	Junction of Rt. 70 and 140. Continue straight on 70.
25.7	0.6	Enter Worcester North quadrangle.
26.1	0.4	Junction of Rt. 70 and Hospital Drive. Continue left on 70.
27.0	0.9	Shrewsbury town line.
27.8	0.8	Worcester town line; junction of Rt. 70 and Plantation St. TURN LEFT onto Plantation Street.
28.2	0.4	Junction of Plantation St. and Lincoln St. Stay straight on Plantation St.
28.4	0.2	Underpass beneath Interstate 290.
28.7	0.3	Stay straight.
28.8	0.1	Sisters of Notre Dame on right. The location of the Carboniferous fossil-bearing Worcester coal mine is on the hill to the right (see Grew, this volume).
29.3	0.5	Outcrops of "Millstone Hill Granite" on hill to right.
29.6	0.3	On left, new University of Massachusetts Medical School.
29.9	0.3	Junction of Plantation St. and Rt. 9 (Belmont St.). TURN RIGHT (west) onto Rt. 9.
30.0	0.1	At Y-intersection, stay right or straight on Rt. 9.
30.4	0.4	Outcrops of "Millstone Hill Granite" on right.
30.6	0.2	TURN RIGHT onto Skyline Drive. Outcrops here and to the south of Rt. 9 by Bell Pond are "Millstone Hill Granite".
31.3	0.7	Outcrops of "Millstone Hill Granite".
31.4	0.1	TURN LEFT just before golf course.
31.6	0.2	Continue past animal farm.
31.9	0.3	Park by stone-framed concession building in Green Hill Park.

STOP 6. Rest Stop and outcrops of "Millstone Hill Granite" and Oakdale Quartzite. From the parking lot, up hill to the southeast are outcrops of "Millstone Hill Granite". Behind the concession stand and along the southeast shore of Green Hill Pond are outcrops of the Oakdale Quartzite, light green-gray, massive, impure quartzite with occasional, thin interbeds and laminae of grey-green quartz-rich phyllite. The Oakdale is particularly quartzitic here.

Return to cars.

32.0   0.1   Proceed to west end of parking lot. Bear right at
             Y-intersection, cross small bridge at end of Green
             Hill Pond and continue up hill.

32.3   0.3   To right on skyline is Worcester Airport, highest
             major airport in the eastern U.S.

32.5   0.2   Exit from park; continue straight on Channing St.

32.7   0.2   Continue straight

32.8   0.1   At T-intersection by the hospital, TURN RIGHT onto
             Kendall St. Proceed one block to Oak St.

32.9   0.1   TURN LEFT onto Oak St.

33.1   0.2   Junction with Rt. 9; TURN RIGHT (west) onto Rt. 9
             (Belmont St.). Get in left lane for entrance to
             Interstate 290 west.

33.15 0.05 TURN LEFT onto access to I290 west, toward Auburn.

33.2   0.05 Large roadcut to left on I290 has contact between
             Oakdale and "Millstone Hill Granite" exposed near
             northern end of cut.

33.8   0.6   Prepare to exit at Exit 14, 122 South, to Posner
             Square and Grafton.

34.1   0.3   Exit 14 off I290. EXIT HERE.

34.2   0.1   Continue straight past first side road on right.
             Outcrop for STOP 7 is on right.

34.3   0.1   T-intersection; TURN RIGHT onto Harrison St.
             Municipal parking lot is on right. Proceed 1/2
             block on Harrison St. to Water St. Enter municipal
             parking lot and park. Walk one block north along
             Water Street to I290 exit.

STOP 7.   Typical Worcester Phyllite of Emerson, (1917); Unit B
          of Grew, (1973); and Unit 3 of Peck, (1976). Rock is a
          dark gray-weathering, shiny light gray phyllite, well-
          foliated, and slightly graphitic. Porphyroblasts of
          biotite have grown across the foliation. Numerous inter-
          beds of graded impure quartzite and quartz-rich phyllite
          from one to several cms. thick are present. The beds
          generally dip to the northwest and grading indicates that
          some beds are overturned. Moderately tight, minor folds
          best seen near the southern end of the outcrop plunge to
          the northwest, have axial surfaces that parallel the
          general bedding direction, and have a cleavage cutting
          bedding in their hinge areas. Please do not climb below
          the access road onto the banks of I290 itself.

Return to cars. From the parking lot, TURN RIGHT onto Water St.

34.4   0.1   At intersection of Water and Grafton St. (first traffic light), Posner Square, CONTINUE STRAIGHT on Water St. and follow sign for Rt. 122 north.

34.6   0.2   At second traffic light, TURN RIGHT onto Franklin St., pass under I290.

34.9   0.3   At Y-intersection beyond the RR crossing, bear left on Franklin Street. Outcrop of Worcester Phyllite is on the right.

35.2   0.3   Park on side of road by A.V. Ricciardi Sweepers Rentals and Catch Basin Cleaning. Outcrops by these buildings, if still accessible, are Pennsylvanian(?).

STOP 8.   These outcrops are believed to be part of the Carboniferous deposits in the Worcester area. Outcrops consist of steeply-dipping, soft, dark gray, graphitic phyllite with several beds of arkose or granule conglomerate up to several cm. thick. Biotite and tiny garnet porphyroblasts are common in the phyllite. Small, highly weathered pebbles in the conglomerate resemble the "Millstone Hill Granite", seen in the hill to the northwest across the railroad yard. Most of the railroad yard is underlain by Carboniferous rocks (See Grew, this volume).

Return to cars. Continue along Franklin St.

35.5   0.3   Outcrops of Worcester Phyllite on right, behind junk yard.

35.8   0.3   Junction of Franklin and Plantation St. at traffic light by fire station. Continue straight across Plantation St. Follow signs to Worcester Science Center.

36.0   0.2   TURN RIGHT onto Harrington Way by playground, second right after crossing Plantation St.

36.2   0.2   TURN LEFT Into Worcester Science Center and park.

STOP 9.   Science Park. By the picnic area at the west end of the parking lot, in a cut for the miniature railroad and by the entrance to the Science Center, the rock is a well-foliated granodiorite with numerous biotite-rich inclusions which are elongated in the plane of foliation. The granodiorite intruded prior to the last metamorphism and is possibly pre-Acadian.

Proceed south to the shore of the swan pond (Beware of the swans; they bite!) where the contact of the foliated

granodiorite and the informally named "Science Park
unit" can be seen. This unit consists of two general
rock types: a rusty-weathering, dark quartz-feldspar-
biotite schist with a few thin coticule layers and a
quartzo-feldspathic gneiss. The "Science Park unit"
occurs between the foliated granodiorite and the Nashoba
Formation in the southern part of the Worcester North
quadrangle and continues south into the Worcester South
quadrangle. It is cut out by the fault at the western
boundary of the Nashoba Formation to the north (Figure
1). This unit is 200 metres thick here at Science Park.
The intrusive contact with the granodiorite is also well-
exposed in the fields to the west of Harrington Way. We
will visit these if time permits.

Proceed southeast around the end of the pond to ledges
south of the Science Center. The "Science Park unit"
here and in the yard by the abandonned house is a feld-
spar-quartz-biotite schist to schistose gneiss, with minor
garnet and sillimanite present. Continue northwest along
ridge to Stegosaurus statue.

From the Stegosaurus, proceed to right (east) downhill past
Polar Bear Plaza, across the miniature railroad track, to
the west shore of the pond, to an exposure of the foliated
granodiorite. Between here and the outcrops to the east of
the pond is a fault trace separating the foliated granodio-
rite and the "Science Park unit" from the Nashoba Formation.
This fault is either the Clinton-Newbury or a related fault.

Continue around the south end of the pond to the outcrops
on the east shore. The rocks here are mapped as Nashoba
Formation and include layered gneiss with alternating
quartzo-feldspathic and biotite-rich layers, biotite
gneiss with feldspar megacrysts to 1 cm., foliated peg-
matite, and small granite and aplite veins. Evidence for
shearing here includes blastomylonitic layers with sheared
and rotated feldspar megacrysts.

Proceed along the east side of the pond and around its
north end to small outcrop on the northwest shore. Here,
thin layers of mylonite, to 2 cm. thick, can be seen in
the foliated granodiorite.

Proceed uphill past the wolf pen to outcrops near the
rear entrance to Science Center building. This is a lens
of rusty-weathering sulfidic quartz-feldspar-biotite schist
in the "Science Park unit."

Return to parking lot and cars. TURN LEFT (south) on
Harrington Way.

36.7   0.5   TURN LEFT at T-intersection onto Hamilton St.

37.3	0.6	Coburn Plaza. Stay straight past basketball court; outcrops of Nashoba Formation in the park.
37.5	0.2	At T-intersection, TURN RIGHT (south) onto Lake Ave.
37.7	0.2	Park along right side of road by large outcrops.

STOP 10. Nashoba Formation. Steeply dipping biotite-rich gneiss and schist with scattered porphyroblasts of feldspar and quartz. The rock here is somewhat more uniform and dark-colored than typical in the Nashoba. Note the presence of pegmatite, sheared pegmatite, and one aplite dike. Sillimanite is present here, although not abundant. The rock is in the sillimanite-K-feldspar zone of metamorphism, although muscovite is still present. A thin layer interpreted as blastomylonite and mylonite occurs near the north end of the outcrop.

Return to cars and turn around. Follow Lake Avenue north 0.5 mile to Route 9. TURN RIGHT (east) onto Route 9 and proceed to Boston, about 35 miles.

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PENNSYLVANIAN ROCKS OF EAST-CENTRAL MASSACHUSETTS

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"that besides our satisfaction as to the Nature of
Vegetation, some further Light, to divers parts of
Knowledge, may likewise hence arise."
                              Nehemiah Grew (1682)

INTRODUCTION

Meta-anthracite, conglomerates, and arkose crop out in iso-
lated exposures along a belt extending northeast from Worcester
to Harvard, Massachusetts (Figures 1 and 2). Of considerable
historical and geological interest is the meta-anthracite out-
crop at the Worcester coal mine, which has yielded plant fos-
sils, that, together with other evidence, have indicated that
these rock units are Pennsylvanian in age. The purpose of this
field trip is to visit some of these exposures, including the
coal mine, and to consider the relations between these rocks and
older metamorphic and plutonic rocks in this part of Massachu-
setts.

The dominant rock types in the exposures that have been
assigned a Pennsylvanian age are phyllite and conglomerate con-
taining pebbles of sedimentary rocks. The outcrops in Harvard
and Bolton (Figure 2) consist entirely of these two rock types,
whereas in Worcester, these rock types crop out only near the
railroad near Shrewsbury Street (Figure 1). These rocks are
generally resistant to erosion and form hills, such as Pin Hill
in Harvard (Stop 4). Arkose and granite-pebble conglomerate, on
the other hand, have only been found in Worcester, where they
were exposed during recent construction (Stop 1). These rocks
are deeply weathered. Meta-anthracite has been found at only one
locality in Worcester (Stop 3).

The phyllite and conglomerate in Harvard and Bolton are gen-
erally referred to as the Harvard conglomerate (or Harvard con-
glomerate lentil); the meta-anthracite is included in the Worces-
ter phyllite (Perry and Emerson, 1903). Hansen (1956, p. 20)
proposed the term Worcester formation to include the Worcester
phyllite, Harvard conglomerate lentil, and Emerson's (1917) Brim-
field schist in the Hudson quadrangle and adjoining areas. Han-
sen (1956) regarded the Harvard as a basal conglomerate to the
Worcester formation, as Crosby (1876) suggested much earlier.
(For a more detailed review of the geology of the Harvard conglom-
erate, see Thompson and Robinson, this guidebook.)

On his map of Massachusetts, Emerson (1917) shows a band of
Harvard conglomerate in Auburn (the next town south of Worcester)
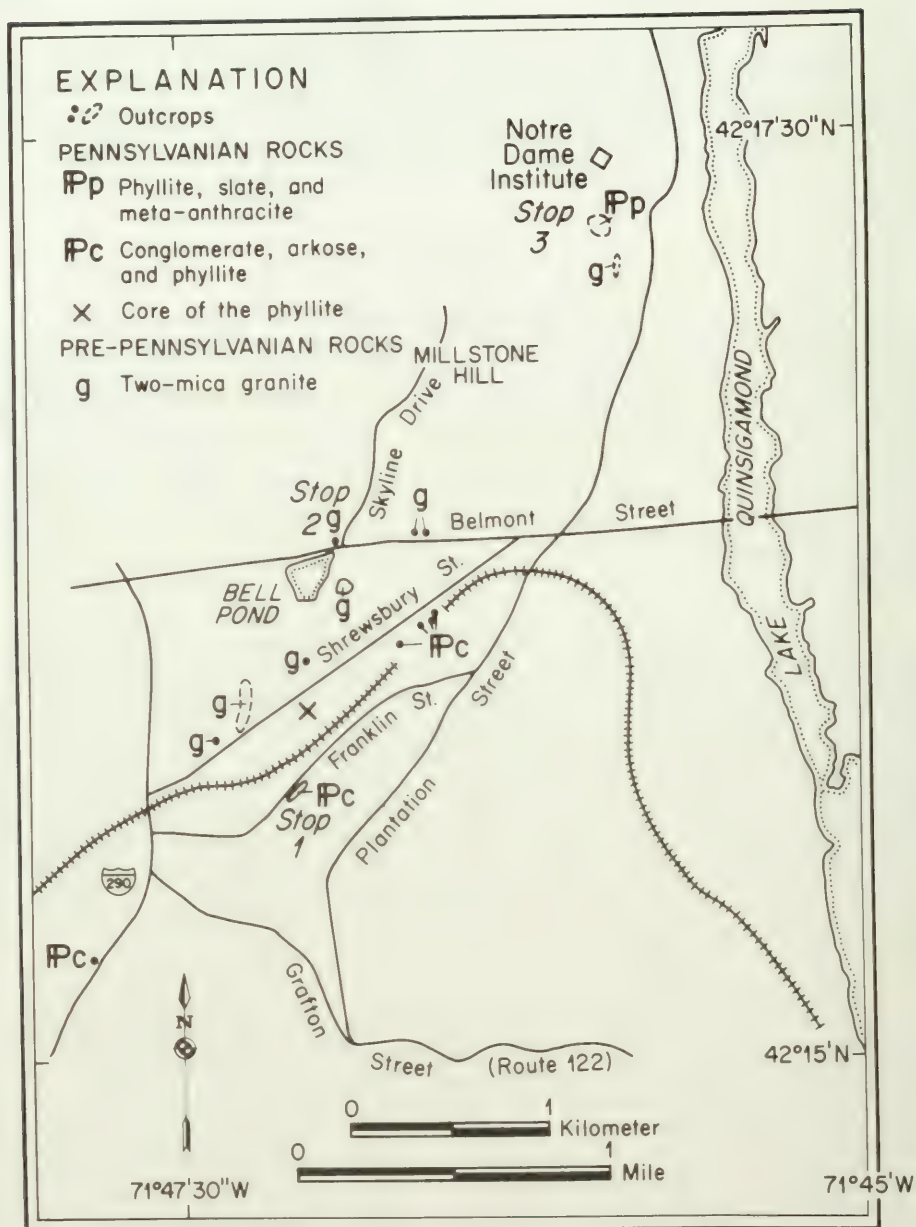in addition to the bands in Harvard and Bolton. Although I made

Figure 1. Sketch map of Worcester, Massachusetts, showing outcrops of Pennsylvanian rocks, outcrops of two-mica granite closest to the Pennsylvanian rocks, and the location of Stops 1, 2, and 3.
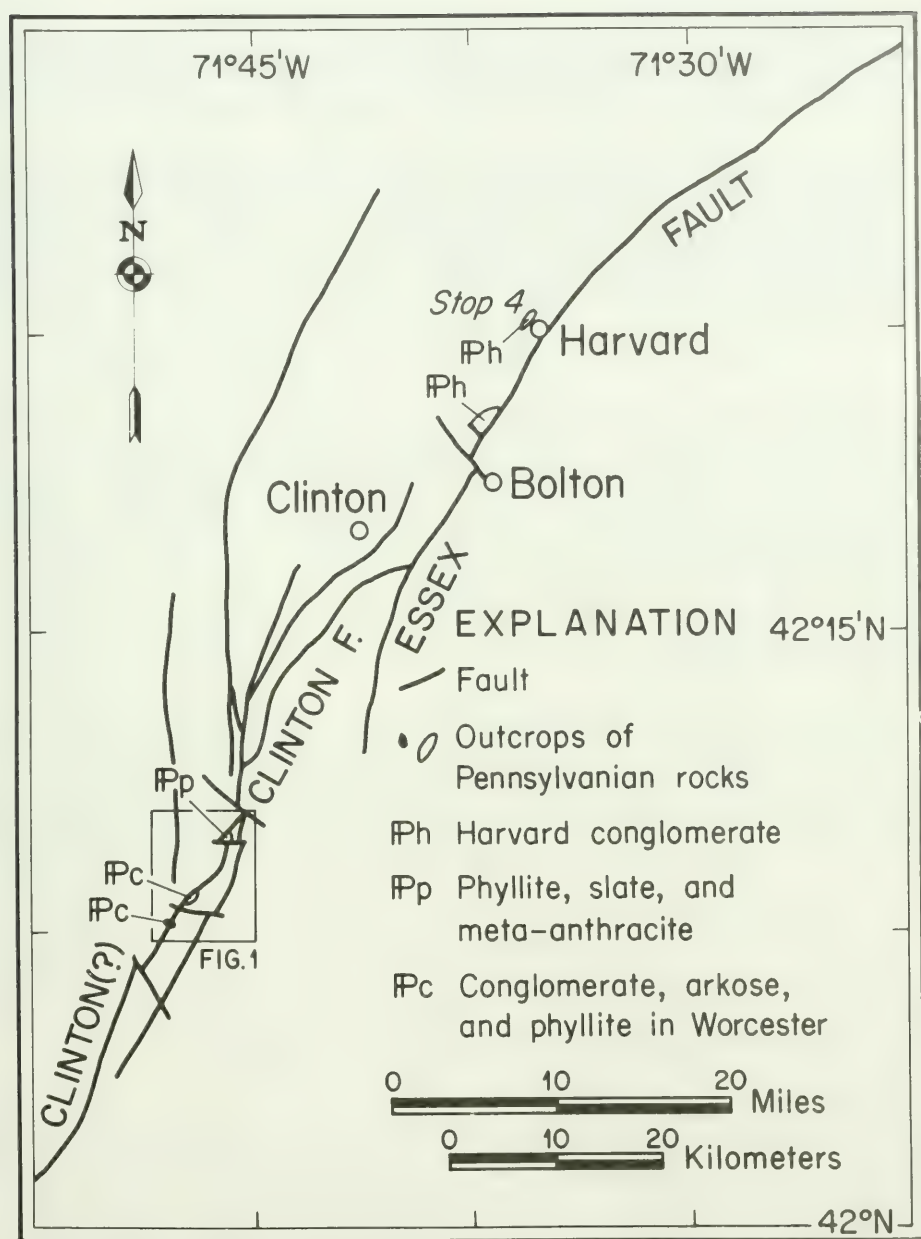
Figure 2. Sketch map of east-central Massachusetts, showing
location of major faults and outcrops of Pennsylvanian rocks,
including Stop 4. Faults are sketched from Castle and others
(1976, plate 1).

an extensive search during mapping, I failed to find any conglom-
erate in Auburn. Perhaps Emerson mislocated the conglomerate
exposed near the railroad in Worcester (Figure 1), which he and
Perry described as a "breccia" (Perry and Emerson, 1903, p.40-41).

The Pennsylvanian rocks in east-central Massachusetts have
been metamorphosed and deformed. Garnet and biotite are found
in the Pennsylvanian rocks in Worcester and chloritoid occurs in
the Harvard conglomerate in Bolton (Hansen, 1956) and Harvard.
Mica schistosity and folded bedding are present in many of the
outcrops of Pennsylvanian rocks in this part of Massachusetts.

AGES OF THE ROCKS AND OF THE METAMORPHISM

The ages and field relations of the meta-anthracite, con-
glomerate, and associated rocks have attracted the interest of
geologists ever since Edward Hitchcock visited the coal mine in
Worcester about 1830. After 1883, several collections of fossils
were made at the coal mine (see below). These fossils have
established the age of the meta-anthracite as Pennsylvanian.
The areal extent of the Pennsylvanian rocks, and their field
relations with the other metasedimentary rocks and with the plu-
tonic rocks in east-central Massachusetts, however, still remain
a subject of controversy.

The basic difficulty encountered in mapping this area is
that there is no obvious structural break or difference in meta-
morphic grade between (1) the meta-anthracite and conglomerates
and (2) phyllites, schists, and quartzites exposed nearby. Fur-
thermore, the phyllites associated with the meta-anthracite and
conglomerate are similar in appearance to other phyllites in this
area. It is thus not surprising that Emerson (1917, p.77-78)
included the metasedimentary rocks of east-central Massachu-
setts in the same stratigraphic sequence as the meta-anthracite
and conglomerates. Not until fossiliferous units were traced
southward from Maine and New Hampshire did geologists in Massa-
chusetts (such as Currier and Jahns, 1952, p. 109) realize that
at least some of the metasedimentary rocks in east-central
Massachusetts must be pre-Pennsylvanian in age.

Recent discoveries in the field suggest that the conglom-
erates are not related to most of the other metasedimentary rocks
in this part of Massachusetts. In Worcester, pebbles of granite
and feldspathic detritus in the conglomerate and arkose are
evidence that this conglomerate is younger than the two-mica
granite on Millstone Hill. This two-mica granite intrudes the
Oakdale quartzite, which conformably underlies the Worcester
phyllite (Emerson, 1917, p.77). In Harvard, the unconformable
relation between the conglomerate and Ayer granite is clearly
shown in a single outcrop (Thompson and Robinson, this guide-
book, fig. 1). The Ayer granite intrudes the Worcester phyllite
and the Boylston schist, which grades into the Worcester (Emer-
son, 1917, p. 68). These relations imply, moreover, that a period

of erosion and uplift followed the emplacement of these granitic rocks and preceded the deposition of the conglomerates. Clearly, some of the Oakdale, Worcester, and related units, all of which Emerson (1917) included in the same sequence as the conglomerates, must actually be much older than the conglomerates.

Geochronologic data on the granitic rocks support these conclusions. Zartman and others (1965) obtained a total rock Rb-Sr isochron age of 345 ± 15 m.y. on the two-mica granite from Millstone Hill, which Zartman (written communication, 1976) has revised to 380 ± 15 m.y. by including more recent analyses on samples he and I collected. Zartman (written communication, 1976) has obtained a U-Th-Pb zircon age of 425 ± 10 m.y. for the Ayer granite in Bolyston (town between Worcester and Clinton), Bolton, and Ayer.

On the basis of the geochronologic ages on the granites, the conglomerate in Harvard is Silurian or younger, and that in Worcester, Devonian or younger. Grew and others (1970, p. 123) concluded that "circumstantial evidence, namely the unconformity below the Pennsylvanian rocks of the Narragansett Basin (Quinn and Moore, 1968) and the lack of any proven post-Pennsylvanian, pre-Triassic (the oldest non-metamorphosed) rocks in southern New England, lends support to the suggestion that the conglomerate [in Worcester] is Late Devonian to Pennsylvanian in age, and that the period of uplift and erosion preceded the deposition of the coal at the Worcester mine." Moreover, the conglomerate crops out within 2.3 km of the coal mine in a direction parallel to the regional trend (Grew, 1973). Thus the conglomerate may belong to the same stratigraphic sequence as the meta-anthracite and, consequently, be Pennsylvanian in age. By analogy, a Pennsylvanian age is also assigned to the Harvard conglomerate in Harvard and Bolton.

In my mapping of the Worcester area (Grew, 1970, 1973), I have included in the Pennsylvanian only the conglomerates, meta-anthracite, and the phyllites immediately associated with the conglomerates and meta-anthracite. In Harvard and Bolton, only the conglomerate-bearing rocks appear to be Pennsylvanian. The other units in Hansen's (1956) Worcester formation and the other units Emerson (1917) considered to be part of the same stratigraphic sequence as the Worcester phyllite are pre-Pennsylvanian in age. According to this interpretation, Pennsylvanian rocks constitute but a small fraction of the metasedimentary rocks of east-central Massachusetts.

The metamorphism of the Pennsylvanian rocks implies that these rocks were at one time deeply buried, suggesting that a thick, and probably extensive, cover of Pennsylvanian sediments was deposited and subsequently removed by erosion after the metamorphism. The present exposures may thus be mere remnants of the deposits in a single basin extending from the area that is now Worcester to Harvard, or beyond, and comparable in size to the Narragansett basin.

The areal extent of rocks affected by the Pennsylvanian or younger metamorphism, on the other hand, may not be significantly larger than the narrow northeast-trending belt in which the Pennsylvanian rocks are presently found. In the Worcester and neighboring areas, metamorphic rocks containing sillimanite and andalusite are spatially associated with two-mica granites, including the Fitchburg (Grew, 1973; Nelson and Kuntz, 1973). As these two-mica granites are probably pre-Pennsylvanian in age, the sillimanite and staurolite zone metamorphism is probably also pre-Pennsylvanian in age. The low-grade metamorphism (garnet, biotite, chlorite zones) in the central part of the Worcester area appears to be contemporaneous with the higher grade metamorphism. In general, there is no textural evidence that these low-grade rocks were derived by retrograde metamorphism of higher grade rocks; these rocks are in fault contact or pass gradationally into the higher grade rocks (Grew, 1973, fig.3). Furthermore, retrograded sillimanite and staurolite zone rocks found in the Worcester area are texturally distinct from the low-grade rocks. A considerable part of the low-grade metamorphism thus may actually be pre-Pennsylvanian in age. The Pennsylvanian or younger metamorphism may have affected only the rocks in the narrow belt in which the Pennsylvanian rocks are found, and could have been responsible for some of the retrograde metamorphism in or near this belt. Folding associated with the Pennsylvanian or younger metamorphism probably also was confined to this narrow belt.

There is no isotopic evidence, moreover, for a widespread regional metamorphic event during the Pennsylvanian or Permian in east-central Massachusetts. Zartman and others (1970, p.3368-3369) did not attribute K-Ar ages of 200-260 m.y. on micas in this area to regional metamorphism. Zartman and others (1965), moreover, report a Rb-Sr age of 360 + 10 m.y. on muscovite from the two-mica granite on Millstone Hill. These authors imply that this granite was not much affected by the Pennsylvanian or younger event that metamorphosed the rocks near the coal mine (Zartman and others, 1965, p. D9).

PENNSYLVANIAN ROCKS AND FAULTS

The geology and field relations of the Pennsylvanian rocks in east-central Massachusetts suggest that the deposition of these rocks was associated with active faulting. The rock types in the Pennsylvanian units are metamorphic equivalents of non-marine sediments such as conglomerate, arkose, and coal, which are characteristic of fault troughs in northeastern North America, as outlined by Klein (1968). Basins typical of the fault trough model, as cited by Klein, include the Narragansett basin (Mutch, 1968) and the Fundy basin (Belt, 1968a). The Pennsylvanian geology of east-central Massachusetts has several other features in common with the Narragansett basin and the Fundy basin, namely thick deposits of non-marine sediments, metamorphism [only "slate grade" in the Fundy basin (Belt, 1968b, p. 109)], and intense

deformation. Moreover, in east-central Massachusetts and around the Narragansett basin (Quinn, 1971, p.51), the pre-Pennsylvanian rocks have been little affected by Pennsylvanian or younger metamorphism and deformation, and in Canada, Carboniferous rocks on platforms surrounding the Fundy basin are little deformed (Belt, 1968b, p. 109).

Mapping in east-central Massachusetts, moreover, has revealed the presence of numerous faults, including the Essex fault system, which extends over 100 km across the state (Castle and others, 1976). A genetic relation between the Pennsylvanian rocks and the Essex fault system is suggested by the fact that the Pennsylvanian rocks crop out along or just west of two faults belonging to that system, namely the Essex and Clinton faults (Figure 2). Castle and others (1976) have suggested that this fault system may have been active in Pennsylvanian time. The deposition of the Pennsylvanian rocks thus might have been related to active faulting along the Essex and related fault systems.

Several authors, notably Wilson (1962), Webb (1969), and Skehan (1969), have suggested that the faults in eastern Massachusetts, including the Essex fault system, might connect across the Gulf of Maine and the Bay of Fundy to the fault systems associated with the Fundy basin rift. Kane and others (1972, p. B18) state that "although the present gravity and magnetic data provide no direct evidence...of a gulfward extension of the rift system of Belt (1968) [1968b], the interpretation of these data [from the Gulf of Maine region] is compatible with the location of structures like these within the gulf."

In conclusion, I propose that the Pennsylvanian rocks and associated faults in east-central Massachusetts represent a continuation of the Carboniferous rift system in eastern Canada. In Massachusetts, most of the Carboniferous sediments have been eroded away, exposing a deeper section of the basin. Only a few outliers of the sediments remain, and these have been metamorphosed as a consequence of their deep burial.

WORCESTER COAL MINE

General History

The first settler of Worcester, Ephraim Curtis, arrived in the fall of 1673. "The principal reason of his selecting this locality...was the supposition of mineral wealth in the soil from the report of a valuable lead mine having been discovered in the vicinity by the Indians" (Wall, 1877, p.33). The Nipmuc (Algonquin) Indians had a fishing settlement on nearby Wigwam Hill, and used the meta-anthracite for face paint. In 1812, "black lead" (plumbago) from Elliot's Worcester Coal Mine was shipped to West Millbury where it was ground in a river mill and was sold for painting house roofs and ship bottoms (Town of Millbury, 1915, p. 261-262; Sandrof, 1948, p.28-29).

In this Bicentennial year, it is appropriate to note that the main source of information about the history of the coal mine is the Massachusetts Spy. This newspaper was established in Boston in 1770; in April, 1775, the press was secretly smuggled to Charlestown, and on May 3, 1775, the first issue of the Spy printed in Worcester carried an eye-witness account of the Battle of Lexington. The editor of the Spy during the height of activity at the coal mine (1823-1829) was John Milton Earle, who was well versed in natural history and took a special interest in the mine.

In 1822, coal from the Worcester coal mine was ceremoniously burned in the presence of the Hon. Levi Lincoln, Governor of Massachusetts. From 1824 to 1827, the Trumbull & Ward Brewery in Worcester burned coal from the mine. In November, 1828, the Spy reported that the mine had been extended 60 feet into the hill at a descent of 25°. Coal was sold for $3 per ton.

In 1829, the Worcester Coal Company and the Worcester Railroad Company were incorporated, the latter to construct two rail lines from the mine: one to Lake Quinsigamond and another to a landing on the recently completed Blackstone Canal from Worcester to Providence. The mine tunnel was extended to a length of 300 feet, and a 400-foot side tunnel was dug for water drainage.

About 1830, "the whole enterprise was abandoned chiefly because, as a wag put it, 'there was a damn sight more coal after burning than there was before'" (Nelson, 1934, p. 351). Nevertheless, after the closing of the mine, Lincoln (1837, p.354) lamented that the coal "which might be made to give motion to the wheels of manufacturing and mechanic industry to unlimited extent, has been permitted to rest undisturbed in its bed."

Notes on Scientific History

For nearly 150 years, the Worcester coal mine has drawn the attention of geologists and paleobotanists in this country and overseas. Edward Hitchcock, apparently the first geologist to visit the coal mine, thought that the Worcester meta-anthracite was older than the Rhode Island anthracite and that there was no "geological connection between the Rhode Island and the Worcester coal" (Hitchcock, 1832, p. 44). Lyell (1844, 1845ab), after visiting the mine on his first trip to North America, was of the opinion that the meta-anthracite in Worcester and the Carboniferour rocks of the Narragansett basin "belonged originally to the same group of sedimentary strata" (Lyell, 1844, p. 215), though fossil evidence was lacking at the time. Later in the 19th century, Louis Agassiz visited the mine and was surprised that no fossils had yet been found. He is reputed to have exclaimed "'Where are the fossils?'" (Perry and Emerson, 1903, p. 18). Agassiz was convinced "that they were there and would be found, if only careful search were made" (Perry and Emerson, 1903, p. 18). This remark inspired a search, and in 1883 Perry found two specimens of Lepidodendron (Perry, 1885). One specimen was examined

by J. D. Dana, who sent a photograph of it to Lesquereux (Perry 1885). Since 1883, more fossils have been collected by Perry (Kemp, 1887), by David White in 1911, by a group led by L. R. Page in 1962, and by Grew in 1968.

Geological Notes

The meta-anthracite in Worcester forms a lens 2 m thick that is exposed only in the coal mine. The lens consists largely of a breccia containing fragments of black slaty rock in a matrix of quartz, muscovite, and chlorite. The remainder of the lens is black slate, which readily breaks into rounded or angular nodular masses, commonly 10 cm across. The surfaces of these masses are shiny, as if polished. In places, the black slate has been crumpled into small folds. The black slate, a very fine-grained tough rock with an earthy luster, contains about 55 percent ash and about 40 percent fixed carbon (Grew and others, 1970; Grew, 1974) and consists of carbonaceous material, quartz, muscovite, marcasite, pyrite, chlorite, and ilmenite. The black slate is commonly cut by veinlets of fibrous chlorite and quartz, with subordinate muscovite and sulfide.

On the basis of published descriptions, J. T. Wilson (1966, p.679) suggested that rocks in the coal mine may be "carbonaceous mylonite" along a fault zone that "marks the line of closure of the Lower Paleozoic Atlantic Ocean." The participants in the field trip may in turn wish to ponder the tectonic significance of the deformation of the meta-anthracite and associated slate and phyllite in the coal mine.

The Pennsylvanian rocks associated with the meta-anthracite and exposed in the outcrops near the coal mine (Figure 3) are carbonaceous (locally also sulfidic) slate and phyllite consisting largely of quartz, muscovite, chlorite, and accessory ilmenite. Marcasite is the dominant sulfide. Garnet is present in the exposures southeast of the mine.

Notes on the Fossils

The nodular masses of black slate commonly break into slabs with flat surfaces. The compressions and impressions of plant fragments illustrated in Grew and others (1970) and in this guide were found on these surfaces. The fossil plant assemblage in my collection from the Worcester coal mine includes calamitean stem fragments (Figure 4), cordaitean foliage (Figure 5), neuropterid pinnules (an example is shown in Figure 6), a Mariopteris-like pinnule, and a Cordaicarpus-like seed (Grew and others, 1970). The most abundant remains are fragments of cordaitean foliage.

In addition to the fossils described by Grew and others (1970), I collected a distinctive fossil of uncertain origin (Figure 7). Qualitative electron microprobe analysis revealed a few grains of apatite in some of the "teeth" of this unidentified fossil.
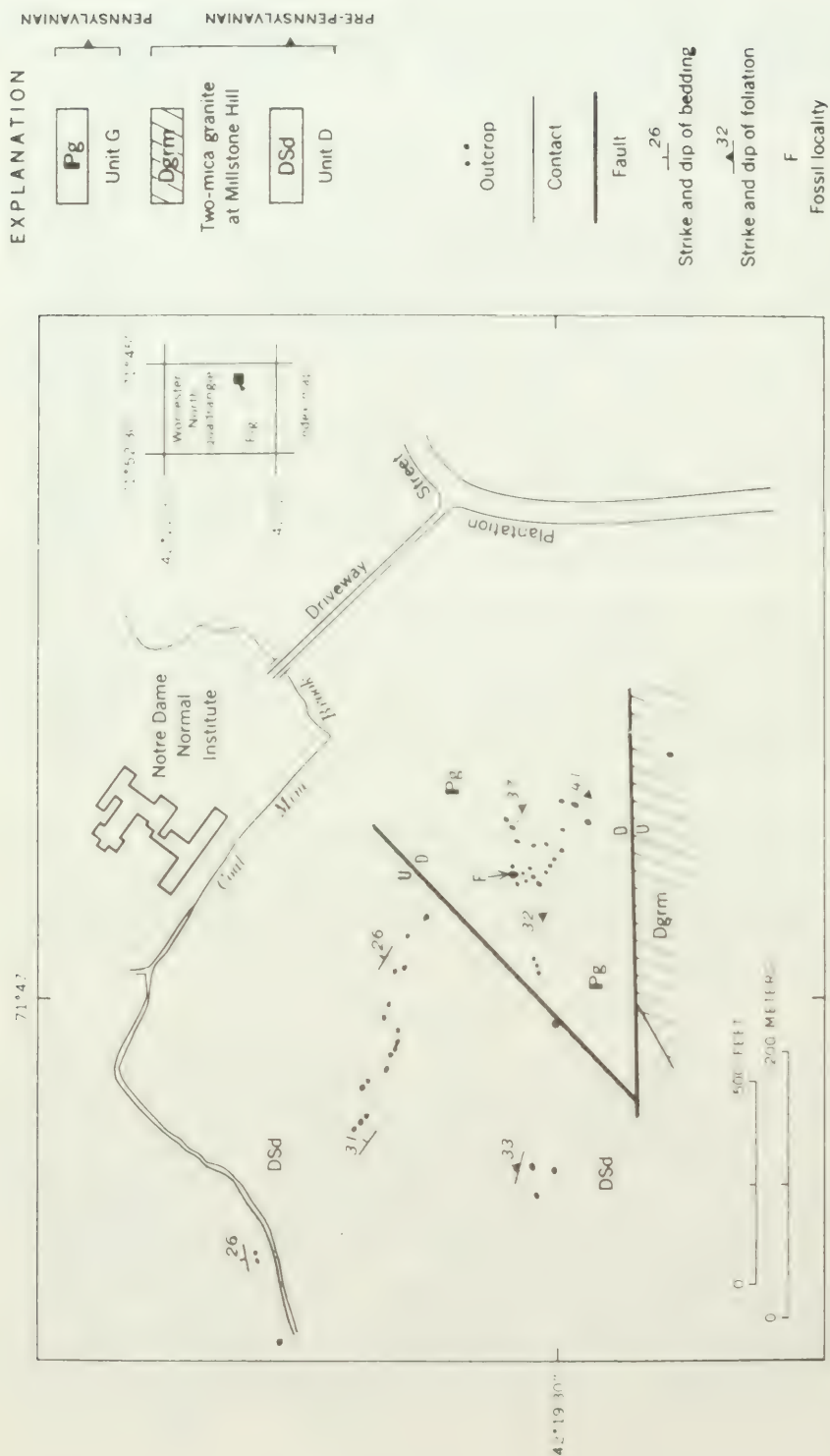
Figure 3. Map showing outcrops in the area around the Pennsylvanian fossil plant locality (F) in the Worcester coal mine (adapted from Grew, 1973, fig. 4). Unit D was mapped by Emerson (1917) as Oakdale quartzite.
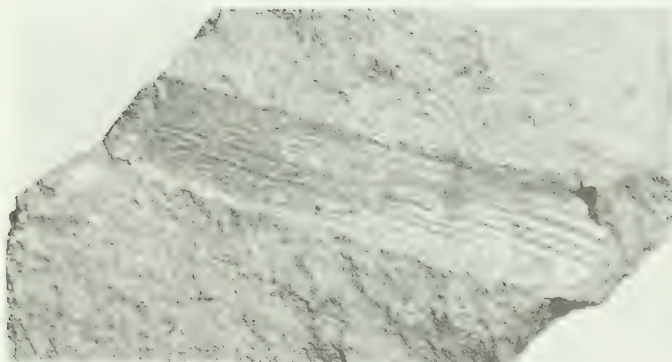
Figure 4. Black slate, Worcester coal mine. Calamites. Stem
    fragment, 4X. Note graphitic film on fossil (from Grew and
    others, 1970, Plate 2B).

Figure 5. Black slate, Worcester coal mine. Cordaites. Fragment
    of leaf, 5X.

Figure 6. Black slate, Worcester coal mine. Neuropterid pinnule, 9X, with basal auriculation and suggestion of a short pedicle (from Grew, 1970, fig.49; cf. Grew and others, 1970, p.121).

Figure 7. Black slate, Worcester coal mine. Unidentified fossil, 9X, possibly a vertebrate jawbone (from Grew, 1970, fig. 50).

I have some doubts concerning the organic origin of the
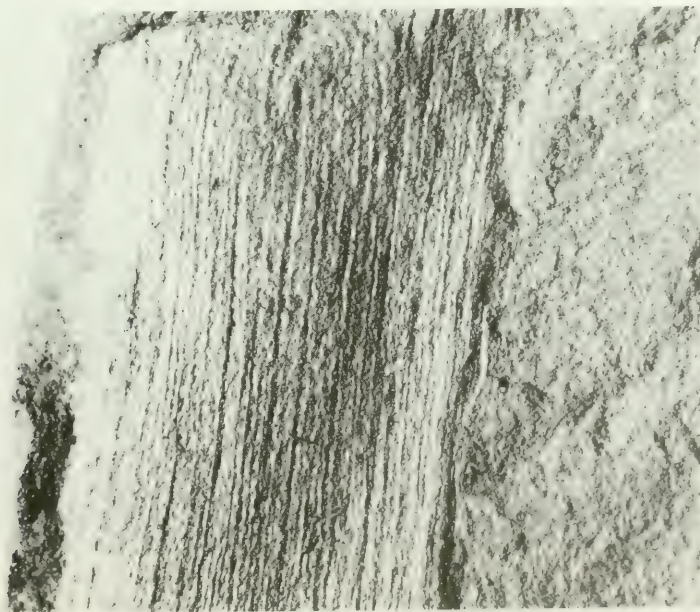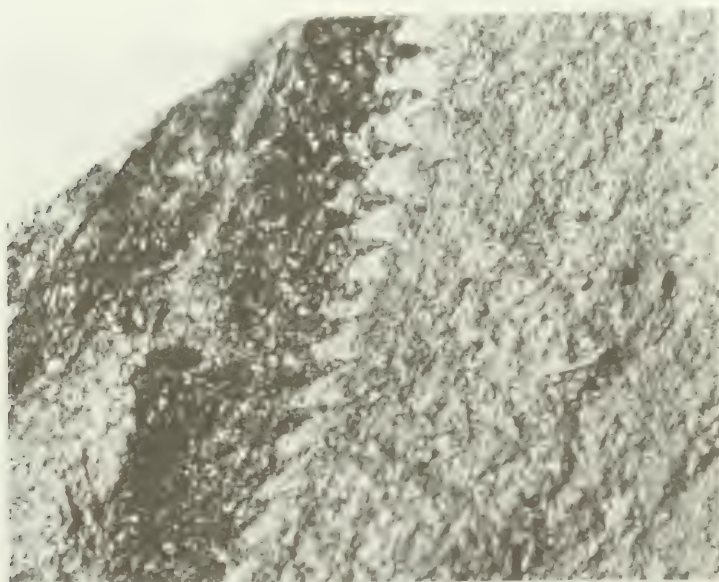helical pattern in Perry's Lepidodendron specimen from the
Worcester coal mine (cf. Billings, 1956, p. 101; Grew,
1970). The ridges bounding the "leaf cushions" are similar to
a lineation defined by the intersection of cleavage and bedding,
which are not parallel in Perry's specimen. Perry's sample is
in a slate similar to that found in the outcrops of Pennsylvan-
ian rocks south and west of the coal mine, but differing from
the black slate in which the other plant fossils were found.

The fossils collected by White in 1911 and by Grew in 1968
leave little doubt as to the approximate age of the meta-anthra-
cite in Worcester. According to Grew and others (1970, p.122),
these fossils "are clearly of Carboniferous age and most likely
of the Pennsylvanian period...most likely early to middle Penn-
sylvanian (Pottsville)" confirming the earlier age assignment by
White (1912). Paul C. Lyons, who has studied the plant fossils
of the Norfolk and Narragansett basins (see Lyons and Chase, this
guidebook), examined a part of my collection and concluded that
the fossils "clearly establish the Pennsylvanian age of the Wor-
cester flora" (Lyons, written communication, 1970).

Because of the poor preservation of the Worcester fossils,
it is not possible with certainty to identify species, or, in
some cases, even genera. Thus some of the identifications made
by Grew and others (1970) are open to alternate interpretation.
Lyons (written communication, 1970) observes that the cordaitean
foliage (such as that illustrated in Figure 5) appears to be Cor-
daites principalis. He further notes that the Calamites illus-
trated in Figure 4 is similar to coarse ribbing that in some
Narragansett basin samples can be traced into venation typical
of Cordaites principalis. He also suggests that the seed (Grew
and others, 1970, plate 1B) may be from a seed fern (possibly
Neuropteris ovata) rather than a cordaicarp, and that the neurop-
terid pinnules that Grew and others (1970, p. 121) considered
"reminiscent of Neuropteris pocahontas" could be a fragment of
N. scheuchzeri. He further states that the pinnule illustrated in
Figure 6 "is definitely a Neuropteris species but the venation
is too obscure for full identification" (Lyons, written communi-
cation, 1970). In summary, Lyons "observed that the better pre-
served fossils [from Worcester] indicate an Alleghenian flora
comparable to that of the Rhode Island Formation..." (Lyons and
others, 1976, p. 183),which he has reported to be closely related
in age to the Westphalian C floras of the Canadian Maritime Pro-
vinces and Europe (Lyons, 1971).

ACKNOWLEDGMENTS

ROAD LOG

Stops 1-3 on this field trip are in the Worcester North 7-1/2 minute quadrangle and Stop 4 is in the Ayer 7-1/2 minute quadrangle. Geologic maps are available for the Worcester area (Grew, 1973) and for the Hudson quadrangle (Hansen, 1956), which lies immediately south of the Ayer quadrangle.

Mileage

0.0 Starting point of road log. Exit 11, Millbury and Route 122, of Massachusetts Turnpike (Interstate 90).

0.3 Turn left on Route 122 for Worcester. Follow Route 122 into downtown Worcester.

3.1 Bear right at traffic light, continue on Route 122 (Grafton Street).

3.6 Follow Route 122 around rotary in Billings Square.

4.0 Go under overpass (Interstate 290) and turn right at traffic light in Posner Square, heading for Washington Square.

4.1 Turn right at traffic light onto Franklin Street, passing under overpass (Interstate 290).

4.4 Bear left at blinking light at intersection, staying on Franklin Street.

4.6 STOP 1. Bus will park in front of Stark Electronics.

Granite-pebble conglomerate, arkose, and carbonaceous phyllite containing garnet and biotite are exposed in weathered cuts around Etre's Auto Body Shop, Stark Electronics, and A. V. Ricciardi's rental establishment. Similar rocks are exposed in a cut along Interstate 290 (Figure 1). The arkose and conglomerate generally occur together in lenses up to 2 m thick in the phyllite. These lenses are found only in the eastern part of the cuts; nearer the road, only phyllite is found. Rock types found in the pebbles of the conglomerate are, in decreasing order of abundance, phyllite, quartzite, granite, and vein quartz. The clasts are up to 13 cm in length. Quartz in the granite pebbles and the matrix of the conglomerate commonly is blue-gray and opalescent.

The beds here strike northeast and dip steeply to the west, a trend which is parallel to that of the pre-Pennsylvanian rocks cropping out east of these exposures (Grew, 1973).

Tough, dark-gray conglomerate crops out between Shrewsbury Street and the railroad northeast of here (Figure 1). The

pebbles consist mostly of quartz-mica schist containing quartz, plagioclase, muscovite, and biotite, and rarely of vein quartz (no granite pebbles have been found).

The hills across the valley to the northwest (including Millstone Hill) are underlain by two-mica granite, which will be examined at the next stop. The granite pebbles and feldspar detritus in the conglomerate and arkose at Stop 1 may have been derived from this two-mica granite. This interpretation is suggested by the proximity of this particular body of granite to the conglomerate and by the presence of blue-gray opalescent quartz both in the granite and in the conglomerate. In the valley itself, at a depth of 28 feet, carbonaceous phyllite was recovered in a drill hole by J. A. Sinnott (Figure 1). This phyllite is included in the Pennsylvanian sequence.

Proceed northeast along Franklin Street.

5.3 At traffic light, turn left onto Plantation Street.

5.7 Plantation Street bridge over railroad. Pre-Pennsylvanian phyllite, coticule-bearing schist, and quartzite exposed in cuts along railroad east and west of bridge.

5.8 At traffic light, turn left onto Belmont Street (Route 9).

6.3 Outcrops of two-mica granite to right.

6.5 Turn right from Belmont Street onto Skyline Drive. Bus will park in lot of Belmont Home near this intersection.

STOP 2. Two-mica granite in road cuts along Belmont Street west of intersection with Skyline Drive.

This rock has been extensively quarried for building stone. In 1733, "the proprietors of the town [of Worcester]...voted that one hundred acres of the poorest land on Millstone Hill be left common for the use of the town for building stones" (Chase, 1879, p.564). By 1837, the quarry was 3 acres in size (Lincoln, 1837, p.355).

The two-mica granite underlying Millstone Hill (Figure 1) is generally a white to light-gray, medium-grained (0.1-7.0 mm) massive rock consisting of quartz, microcline-perthite, and albite, with accessory muscovite, biotite, chlorite, garnet, epidote, carbonate, apatite, and fluorite.

Features to note in these road cuts are blue-gray opalescent quartz, aplite veins, and cataclastic zones. The cataclastic rocks in these zones, here and elsewhere in the granite body, resemble quartzite and phyllite. One of the "phyllite inclusions" described by Perry and Emerson (1903, p.58-59), which

was still accessible in 1967, is actually a cataclastic rock derived from the granite.

Emerson (1917) mapped the two-mica granite as Ayer granite. It differs from typical Ayer, which we will examine at Stop 4, by its lack of feldspar megacrysts and by the presence of widespread accessory fluorite. The two-mica granite at Stop 2 may in fact be younger than the Ayer. Zartman (written communication, 1976) has obtained a Rb-Sr isochron age of 380 ± 15 m.y. on the two-mica granite of Millstone Hill and a U-Th-Pb age of 425 ± 10 m.y. on porphyritic Ayer.

From parking lot, exit onto Skyline Drive and turn left immediately on Belmont Street. Return along Belmont Street back to Plantation Street.

7.2 Turn left at traffic light onto Plantation Street.

7.7 Small outcrops of pre-Pennsylvanian quartz-mica schist along Plantation Street. Millstone Hill to left; to right (east) is Wigwam Hill, which is underlain largely by pre-Pennsylvanian coticule-bearing rocks. Wigwam Hill was the site of a Nipmuc (Algonquian) camp near the fishing waters of Lake Quinsigamond and the plumbago deposit of the coal mine.

8.2 Turn left at entrance to Notre Dame Institute, which can be recognized by stone pillars supporting a large sign over driveway, "Sisters of Notre Dame de Namur."

8.45 Parking lot of Notre Dame Institute. Comfort facilities are available in the basement of the hospital.

STOP 3. Area of the Worcester Coal Mine.

Proceed southeast on foot, crossing Coal Mine Brook on footbridge and following edge of field for 500 feet. Turn right at wooded rise in field and proceed 300 feet west-southwest through woods up hill to coal mine. (Lunch here, weather permitting.)

Meta-anthracite, slate, and phyllite of Pennsylvanian age are exposed only in the small gully near the coal mine (see text). These exposures are bounded to the northwest by calc-silicate rocks and biotite schist [part of Emerson's (1917) Oakdale quartzite], to the south by two-mica granite, and to the east by surficial deposits. The contacts of the Pennsylvanian rocks with the surrounding rocks are not exposed.

Calc-silicate rocks and purplish-gray to gray biotite schist crop out on the hill and along a brook northwest of the coal mine (Figure 3). The calc-silicate rocks are typically green-gray and consist mostly of quartz, plagioclase,

K-feldspar, biotite, calcic amphibole, and iron-poor epi-
dote. Diopside has been found in similar rocks elsewhere
in the Worcester area.

Return along driveway of Notre Dame Institute to entrance at
Plantation Street.

8.7 Turn left and proceed north on Plantation Street.

9.3 At light, turn right onto Lincoln Street.

9.5 Shrewsbury-Worcester Town Line. Proceed east along West Main
Street, Shrewsbury, which is the continuation of Lincoln
Street, Worcester.

9.7 North end of Lake Quinsigamond. Quinsigamond is an Algon-
quian name (Rice, 1893, p.87) meaning fishing place for
pickerel (a pike). Quaternary deposits and the present lake
fill a deep Tertiary river valley (Alden, 1925, fig.3). In
drill holes under the bridge for Interstate 290 over the
lake, bedrock was reached at depths as much as 181 feet be-
low the present surface of the lake, that is, 77 feet
above sea level.

10.0 Proceed under overpass in left lane and take Interstate 290
east towards Marlboro. In entrance ramp are cuts in the
pre-Pennsylvanian Nashoba formation. The Nashoba formation
in this area consists largely of biotite gneiss with subordi-
nate migmatitic gneiss and augen gneiss.

11.7-13.3 Road cuts of Nashoba Formation.

19.8 Interstate 290 ends. Take Interstate 495 north towards
Lowell.

29.7 Exit 16 for Route 111, Harvard and Boxborough. Go right on
Route 111 toward Harvard.

30.2 Road cuts of Nashoba formation (Hansen, 1956).

32.5 Bear right on Route 111, proceed along it into Harvard.

32.8 At traffic light, continue straight on Route 111.

33.2 Turn left on Harvard Depot Road (marked by sign for Tensi-
tron). Pin Hill, directly ahead, is the site of numerous
small quarries. Whitney (1793, p.156) reported that slate
at Pin Hill was quarried for tombstones, door jambs, and
hearthstones.

33.4 Crest of Pin Hill is Harvard conglomerate, which we will
examine.

33.6 Intersection of Harvard Depot Road with Mill Road. Visible
up Mill Road to the right is a brick mill house about 300
years old. Bus will turn left into Sanitary Landfill dump
and park.

STOP 4. Ayer granite and Harvard conglomerate.

Proceed on foot to outcrop of Ayer granite at corner of Mill
Road and Harvard Depot Road. The porphyritic Ayer granite
in this outcrop (see also Thompson and Robinson, this
guidebook) consists of microcline, saussuritized plagio-
clase (An 10), and quartz, with accessory biotite, chlor-
ite, muscovite, clinozoisite, apatite, and zircon, The
feldspar and quartz are cut by microveinlets of quartz.

Zartman (written communication, 1976) has obtained Pb-Pb
ages on zircon of 422 and 432 m.y. on a sample collected
about 4 miles north of here in the same body of Ayer as
this outcrop.

Proceed east along Harvard Depot Road to Pin Hill. We will
examine the outcrops along the road (WATCH FOR TRAFFIC) and
the unconformity in the woods to the north. A detailed
description of the Harvard conglomerate and of the unconform-
ity at Pin Hill, including a fine sketch of the unconformity
by Peter Robinson, is contained elsewhere in this guidebook
(Thompson and Robinson, fig. 1). NO HAMMERS ON THE OUTCROP
OF THE UNCONFORMITY, PLEASE!

Return on foot to bus. For the return to Boston, bus will
retrace route along Harvard Depot Road back to Route 111.

34.0 Turn left and head north on Route 111.

35.1 Route 2. Head east for Boston. End of road log.

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Trip B-18

COAL STRATIGRAPHY AND FLORA OF THE NORTHWESTERN NARRAGANSETT BASIN

by

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and

Harry B. Chase, Jr.
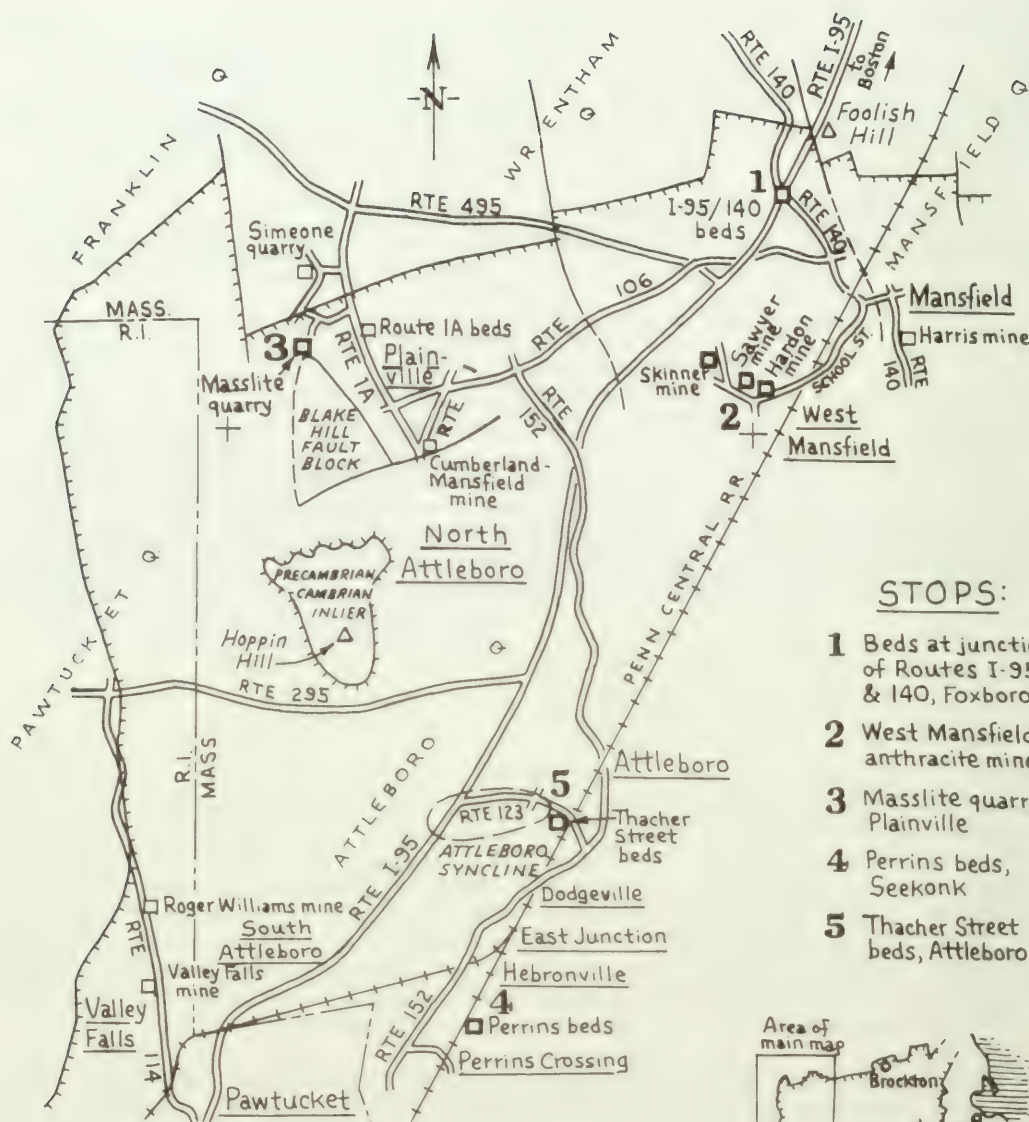The Foxboro Company
Foxborough, MA 02035

The energy shortage of recent years, which has severely affected New England, has resulted in renewed interest in coal exploration in the Narragansett basin. Shaler and others (1899, p. 134) divided the strata in the northern field of the Narragansett basin into the following units [names modified from Emerson (1917)], from top to bottom:

Dighton Conglomerate.	1,000-1,500 ft
Rhode Island Formation.	.10,000 ft
Wamsutta Formation	1,000 ft
Pondville Conglomerate.	100 ft

An excellent summary of the geology of the basin is in Quinn and Moore (1962). Five stops will be made to illustrate the stratigraphy and flora of the northwestern part of the basin (Fig. 1), an area of continental clastic rocks and coal of Pennsylvanian age. The Rhode Island Formation, the sole focus of this field trip, underlies about 70 per cent of the area of the Narragansett basin. It is the only stratigraphic unit that contains mineable amounts of coal and its plant fossil assemblages can be used to establish distinct time zones over a thick stratigraphic sequence. There will be opportunities to collect samples of coal and fossil plants and to see sedimentary and structural features and lithologic and metamorphic variations in this formation.

STOP 1. Foxborough beds, Foxborough, MA, Interstate 95 and Route 140. Park on Route 140 southbound, north of I-95. Watch out for traffic.

This area is an important exposure of a large section of the Rhode Island Formation (Fig. 2) with a minimum of 1400 stratigraphic ft of strata, including a buried series of 13 coal beds (Fig. 3A). The geology is complex due to faulting, primary and secondary folding, and probable facies changes which make correlation of beds most difficult. The section is cut through by a fault crossing Route 140 beneath I-95 that may be the southward continuation of the Stony Brook Fault from the Norwood quadrangle (Chute, 1966). It is indicated by shears, quartz veins and breccia, occurring in a zone up to about 70 ft wide. This fault has its origin in the Boston Basin (Billings, 1976). The coal beds have an average strike of N45°W and dip of 48°SW. They could not be traced more than 120 ft to the northwest, probably due to faulting.

MAP OF THE NORTHWEST NARRAGANSETT BASIN, MASS. & R.I.

-N-

WRENTHAM Q

RTE 140 RTE I-95 to Boston

Foolish Hill

RTE 495

FRANKLIN Q

Simeone quarry

MASS. R.I.

1 I-95/140 beds

RTE 140

106

RTE 140 Mansfield

School St RTE 140 Harris mine

Route IA beds

Plainville

3 Masslite quarry

RTE IA

RTE

Skinner mine Sawyer mine Hardon mine

BLAKE HILL FAULT BLOCK

RTE

RTE 152

Cumberland-Mansfield mine

2 West Mansfield

North Attleboro

PRECAMBRIAN CAMBRIAN INLIER

Hoppin Hill

Q

PENN CENTRAL RR

RTE 295

STOPS:

1 Beds at junction of Routes I-95 & 140, Foxboro

2 West Mansfield anthracite mines

3 Masslite quarry, Plainville

4 Perrins beds, Seekonk

5 Thacher Street beds, Attleboro

PAWTUCKET Q

RTE I-95

ATTLEBORO

RTE 123 **5** Attleboro

ATTLEBORO SYNCLINE

Thacher Street beds

Dodgeville

R.I. MASS

Roger Williams mine

South Attleboro

East Junction

Valley Falls mine

Hebronville

RTE 152

4 Perrins beds

Valley Falls

RTE 114

Perrins Crossing

Pawtucket

FIG. 1
MAP OF THE NORTHWEST
NARRAGANSETT BASIN,
MASS. & R.I.

0 _____ 5 MILES
0 _____ 7 KILOMETRES

Area of main map

Brockton

Plymouth

Providence

Fall River

THE NARRAGANSETT BASIN
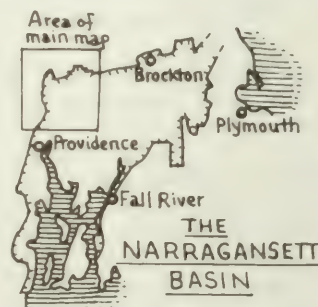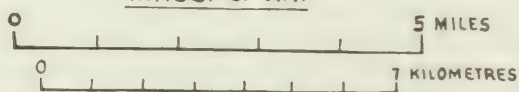
(Modified from Shaler & others, 1899)
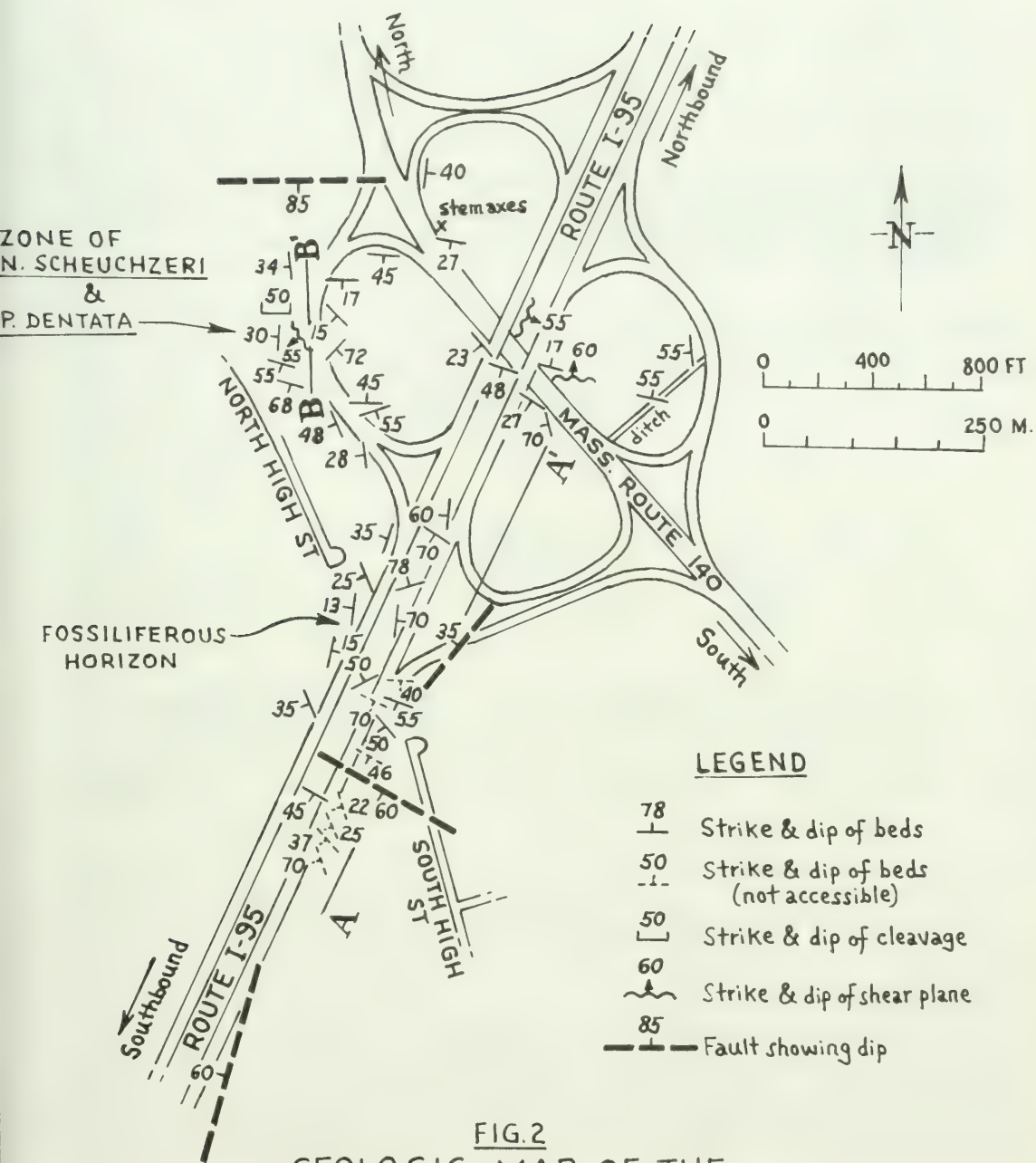
FIG. 2
GEOLOGIC MAP OF THE
RHODE ISLAND FORMATION,
ROUTES I-95 & I40,
FOXBOROUGH, MASSACHUSETTS

CORDAITES PRINCIPALIS   CORDAITES

1 2 3   4 5 6 7   8   9   10   11   12 13

No exposure

LEGEND ▷ [Shale] Shale   [Sandstone] Sandstone   / Fault

Anthracite coal beds are numbered 1-13

0   100   200   300 FEET

0   100 METRES

FIG 3A
COAL BED SERIES

Light to medium
gray siltstone,
slaty cleavage
dips 50° N

Dark gray
fossiliferous
mudstone,
slaty cleavage
dips 43° NW

Gray, fine pebble
conglomerate

Slaty
cleavage

Secondary folds,
axial plane
dips 66° NW

RELATION OF
SECONDARY FOLDS
& SLATY CLEAVAGE

B   B'

Bedding

Secondary folds,
axial plane
dips 60° NW

6-inch
coaly bed &
4-inch quartz
vein

Fossiliferous
laminated
siltstone

Pavement
drain

Bedding

Coaly shale bed
in zone of minor folds
& quartz veins
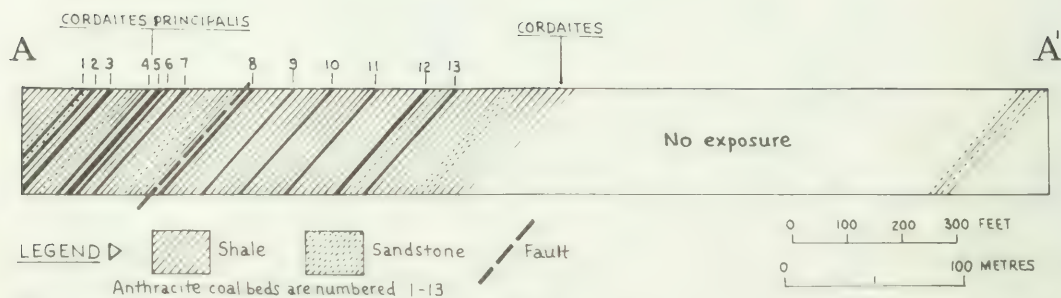
Slaty
cleavage
dips 69° NW

0   50 FEET
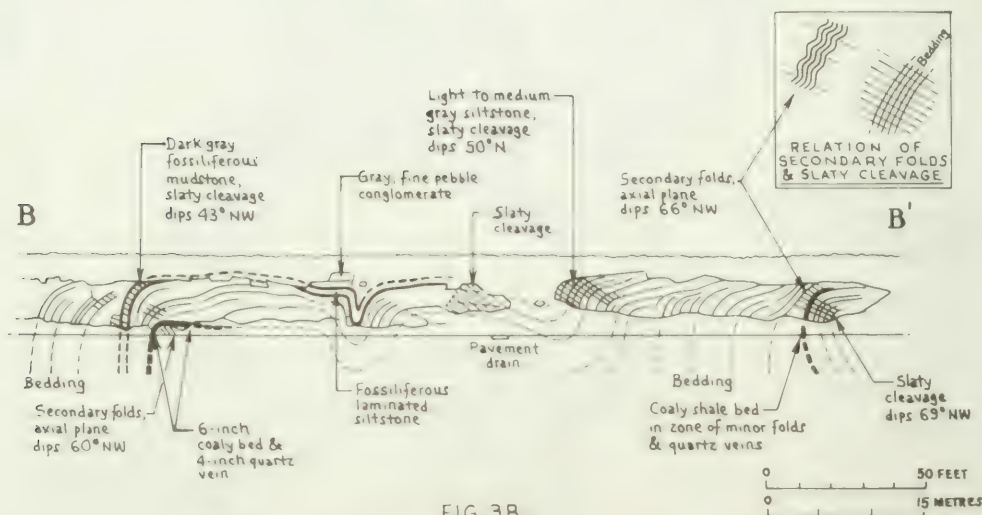
0   15 METRES

FIG 3B
VIEW OF FOLDED SEQUENCE ON WEST RAMP

FIG. 3
SECTION A-A' & VIEW B-B' FROM FIG. 2
RHODE ISLAND FORMATION,
ROUTES I-95 & 140, FOXBOROUGH, MASSACHUSETTS

In 1964, Chase mapped a 650-ft thick section of the Rhode Island Formation, including 13 coal beds (Fig. 3A) occurring over a stratigraphic thickness of 450 ft, exposed during highway excavation of the east wall of I-95 northbound near South High Street (Fig. 2). Coal beds 3 and 12 are 4 1/2 ft thick; coal bed 8, 4 ft thick; coal beds 2 and 5, 3 ft thick; other coal beds are 1 to 2 1/2 ft thick. The 13 coal beds total 30 to 35 ft in stratigraphic thickness. Cordaites principalis was noted (Chase, 1964, unpub. data) in the beds directly below coal bed 4 and in coal bed 5, and other plant fossils were noted below coal beds 1 and 7 (Fig. 3A). Neuropteris(?) and C. principalis were also found on the west side of I-95 southbound, opposite North High Street (Fig. 2).

North of this fossiliferous zone is the fossil locality of Lyons (1969) where a Westphalian C flora was discovered (Fig. 2, 3B; Table 1). Here a fossiliferous zone occurs stratigraphically above a 14th coal bed, 0.5 ft thick, first noted by Roger F. Mullen of Mansfield and Daniel Murray of Boston College (verbal commun. to Chase, 1975-76). These beds are part of a large recumbent fold (probably a slump structure) characterized by small plunging secondary folds with associated slaty cleavage and quartz veins (Fig. 3B).

The typical coal found by Chase was medium- to medium-dark gray, laminated, submetallic to very lustrous, fragmental-looking, with a blocky fracture and penetrated by quartz veinlets. Five samples collected have an average specific gravity of 1.99, indicating a high ash content. [A nearby coal from the abandoned Crehore mines was analyzed at 18% ash content (Hitchcock, 1841, p. 134).]

In May 1975 we mapped in detail the bedrock geology of the presently exposed beds in this area (Fig. 2). Over a dozen faults, indicated by slickensides, quartz veins, breccia and shear zones were mapped. There are two dominant complimentary fault sets in this area, one striking N15-20°E and another striking N15°W, which are probably related to north-south stress. The average strike of the beds is N40°W and the average dip is 45°SW.

The lithology is predominantly graywacke and dark gray shale and mudstone. Polymictic pebble conglomerate in beds up to 2 ft thick, bluish gray and laminated siltstone, and mottled "claystone" were also mapped. A dark-brownish coal with blocky fracture was mapped and correlated with coal bed 10. The fine-grained graywacke is typically light gray, pin-striped (in places convoluted), cross-bedded, and well indurated. Rip-up clasts of mudstone can be seen in it on the east side of Route 140. In places, up to about 20 modal per cent feldspar and specks of muscovite were observed in this graywacke. The coarser graywacke is commonly pebbly with conspicuous grains of muscovite and feldspar and has coaly stem axes. The latter are generally oriented east-west, probably indicating local drainage from the west. Similar lithologic sequences containing conglomerate beds were mapped, but it is not clear whether this is due to structural complexities or cyclic sedimentation.

Lyons (1969) described and illustrated most of the fossils from this locality. Approximately 30 species are now recognized (see Table 1). Very good specimens of Cordaites principalis, Neuropteris scheuchzeri, Pecopteris dentata, Neuropteris heterophylla (Fig. 4A), and Lepidostrobophyllum majus (Fig. 4B) can be collected here.

<u>TABLE 1. FOSSIL FLORA OF THE NORTHWESTERN NARRAGANSETT BASIN, MASSACHUSETTS</u>

Species	Masslite	Foxboro[5]	Hardon	Sawyer	Skinner	Perrins
1. *Annularia acicularis*	R[1]	R	-	-	-	-
2. *A. mucronata*	R[1]	-	-	-	-	-
3. *A. sphenophylloides*	R[1]	C	R	-	-	C[2,4]
4. *A. stellata*	-	-	C	C	-	-
5. *Asterophyllites equisetiformis*	R	C	C	C?	-	R
6. *Alethopteris serlii*	R	-	C	-	-	R
7. *A. grandini*	-	-	-	-	-	R[4]
8. *Calamastachys* cf. *germanica*	R	-	cf.	-	-	C
9. *Calamites carinatus*	R[1]	-	C	-	-	?
10. *C. cistii*	C	-	-	?	-	C
11. *C. scheuchzeiformis*	-	-	R	-	-	C
12. *C. suckowi*	R	-	R	-	-	R[3]
13. *C. undulatus*	R[1]	-	-	-	-	-
14. *Cordaites communis*	-	-	-	-	-	R[3]
15. *C. principalis*	C	C	C	C	C	C
16. *Crossotheca sagittata*	R	-	-	-	-	-
17. *Cyclopteris trichomanoides*	C	-	-	-	-	-
18. *Eremopteris lincolniana*	R[1]	-	-	-	-	-
19. *E. missouriensis*	R	R	R[3]	-	-	-
20. *Lepidodendron* cf. *lanceolatum*	R[1]	-	-	-	-	-
21. *Lepidophylloides brevifolium*	-	-	-	-	-	C
22. *L. mansfieldi*	R	R	-	-	-	-
23. *Lepidostrobophyllum majus*	C	C	-	-	-	-
24. *Mariopteris nervosa*	C	C	R	-	C?	-
25. *Neuropteris* cf. *agassizi*	-	-	-	-	-	R[4]
26. *N. desorii*	-	-	-	-	-	R[4]
27. *N. fimbriata*	-	-	-	-	-	C
28. *N. heterophylla*	C[1]	C	C	?	-	-
29. *N. obliqua*	-	-	R	-	-	R
30. *N. ovata*	-	R	-	-	-	-
31. *N. rarinervis*	-	C	C	-	-	-
32. *N. scheuchzeri*	C	C	C	C	-	-
33. *N. tenuifolium*	-	C	R	-	-	-
34. *Odontopteris reichiana*	-	-	-	-	-	C[4]
35. *Pecopteris abbreviata*	R	C	-	-	-	-
36. *P. arborescens*	-	-	-	-	-	C[4]
37. *P. clarkii*	R[1]	-	-	-	-	-
38. *P. dentata*	-	C	R	-	-	-
39. *P. feminaeformis*	-	-	-	-	-	R[4]
40. *P. hemitelioides*	R[1]	-	-	-	-	-
41. *P. lamuriana*	-	R	R	-	-	-
42. *P. miltoni*	R	R	C	C	-	-
43. *P. polymorpha*	-	-	-	-	-	R[4]
44. *P. unita*	-	-	R	-	-	-
45. *Sphenophyllum cuneifolium*	C	C	C	-	-	-
46. *S. emarginatum*	C	C	R	-	-	-
47. *S.* cf. *longifolium*	R[1]	-	-	-	-	-
48. *S.* cf. *majus*	-	R	-	-	-	-
49. *S. oblongifolium*	-	-	-	-	-	?C[4]
50. *Sphenopteris capita*	-	-	-	-	-	R[3]
51. *S. hirticula*	R[1]	-	-	-	-	-
52. *S. obtusiloba*	-	-	R	-	-	-
53. *S. striata*	R	-	-	-	-	cf.[3]
54. *Stigmaria ficoides*	C	-	-	-	-	-

R=rare (<1%); C=common (≥1%); ?=uncertain; -=absent or not known; cf.=conforming to.

1, Oleksyshyn (1976); 2, Round (1924); 3, Round (1927); 4, Darrah (1970);
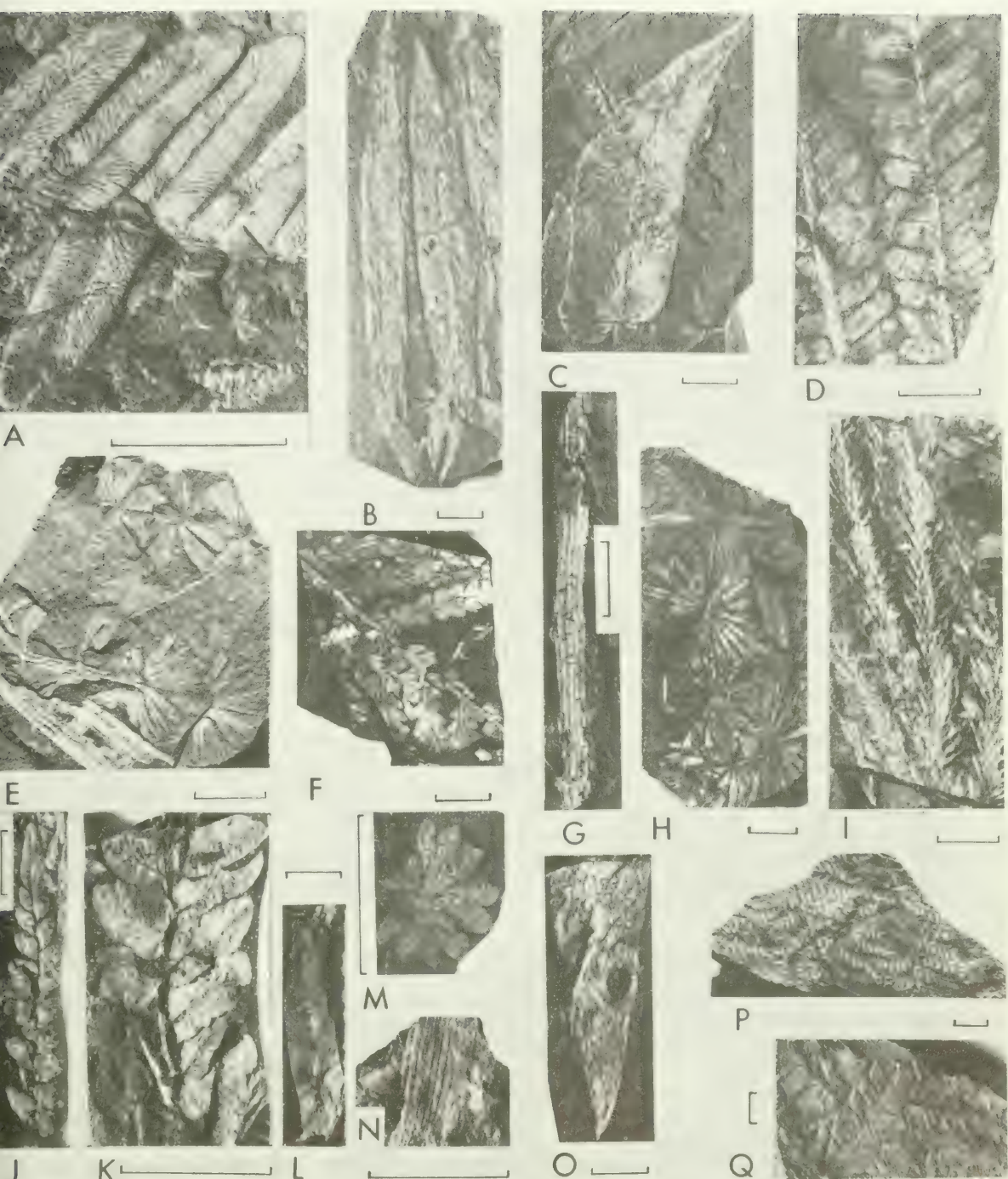5, Lyons (1969).

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Figure 4. Flora of the northwestern Narragansett Basin. A, *Neuropteris heterophylla* Brongniart (F-100); B, *Lepidostrobophyllum majus* Brongniart (F-56); C, *Neuropteris scheuchzeri* Hoffman (H-144); D, *Pecopteris lamuriana* Heer (H-69A); E, *Sphenophyllum cuneifolium* Sternberg (H-27b); F, *Mariopteris nervosa* Brongniart (H-126); G, *Calamites carinatus* Sternberg (H-27b); H, *Annularia stellata* Wood (H-89A); I, *Lepidodendron* cf. *lanceolatum* Lesquereux (Pl-36); J, *N. heterophylla* Brongniart (Pl-32); K, *N. hetero-phylla* Brongniart (Pl-35); L, *N. scheuchzeri* Hoffman (Pl-33); M, *Annularia spheno-phylloices* Zenker (Pl-145); N, *Cordaites principalis* Germar (Pl-27); O, *C. principalis* Germar (Pl-30); P, *Mariopteris nervosa* Brongniart (Pl-34); Q, *Odontopteris reichiana* Gutbier (PC-17A). A, B: Foxborough; C through H: Hardon Mine, Mansfield; I through P: Masslite quarry, Plainville; Q: Perrins Crossing, Seekonk. Scale equals 1 cm.

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The fossil assemblage is indicative of the Lower Allegheny subseries which is equivalent to Lower Westphalian C of Maritime Canada and western Europe (Lyons, 1969, 1971). The Foxborough plant fossils are probably slightly younger than the Masslite plant fossils and slightly older than the fossils found at the Hardon Mine. All three fossiliferous strata are referred to Westphalian C.

STOP 2.   Coal mines, West Mansfield, MA. Please respect private property
           and watch out for poison ivy.

West Mansfield is the oldest and most important coal mining area in Massachusetts (Figs. 1, 5). Chute and Currier (1942) sketched the history of the Mansfield mines and described the coal and the coal beds. The Hardon and Skinner mines were opened in 1835 (Fig. 5B), but both mines failed financially and were closed in 1838. Attempts to reopen the Skinner mine in 1923 and 1925 failed. The Sawyer mine was worked from 1848 to 1854 by Benjamin F. Sawyer of New York. In the 1880's a company headed by N. S. Shaler traced the Hardon main coal bed by means of drilling to a depth of 850 ft. In 1910 a new company sank a slope shaft on the Hardon main coal bed (Fig. 5B), which was worked sporadically until 1923, but little coal was produced.

About 7000 tons of fair-quality anthracite were mined at Mansfield. The coal was used in the mine engines and locally for heating and smelting. Over the years the shafts have been filled. Most of the Hardon and Skinner waste dumps have been removed, but at Sawyer's 5000 tons of fossiliferous rock remain.

The mines failed for the following reasons: (1) insufficient ex- ploration and development; (2) insufficient capital; (3) inexperienced manage- ment; (4) expense of pumping water; (5) expense of tracing and working the thin, irregular, steeply-dipping coal beds; (6) inadequate preparation plant; (7) poor performance of the coal in comparison with competing fuels; (8) popu- lar prejudice against the coal, and lack of understanding of how to use it; (9) mining out of the accessible coal beds; (10) national economic depression coinciding with mining efforts.

Following the fuel shortages of 1973-4, private, state, and federal investigators have considered Mansfield anthracite as a potential source of energy. In 1974 the U. S. Bureau of Mines made calorimeter tests and proximate analyses of coal from the mine dumps (Fed. Energy Admin., 1975). New drilling has been proposed (Sacks, 1975, p. 4).

The coal beds occur in a 4000-ft thick stratigraphic interval on the south limb of a probable syncline (Fig. 5A). The coal, slate, shale, sand- stone, and pebble conglomerate beds of the Rhode Island Formation of these mines strike ENE and dip 30° to 80° (average 55°) NNW. In the Hardon mine the dip increases with depth (Fig. 5B). Of the 18 to 20 known coal seams (Fig. 5A), 7 were of sufficient thickness and continuity to be worked: the Hardon back, main, and front beds (Fig. 5A, 5B); the Sawyer South Seam (location presently unknown) and North Seam (Fig. 5A); and the Skinner Wading Vein and one of the Skinner front beds (Fig. 5A, C). The 7 Hardon coal beds may be equivalent to the lower of the 13 Sawyer coal beds (Fig. 5A). The "Segerbrand coal bed"
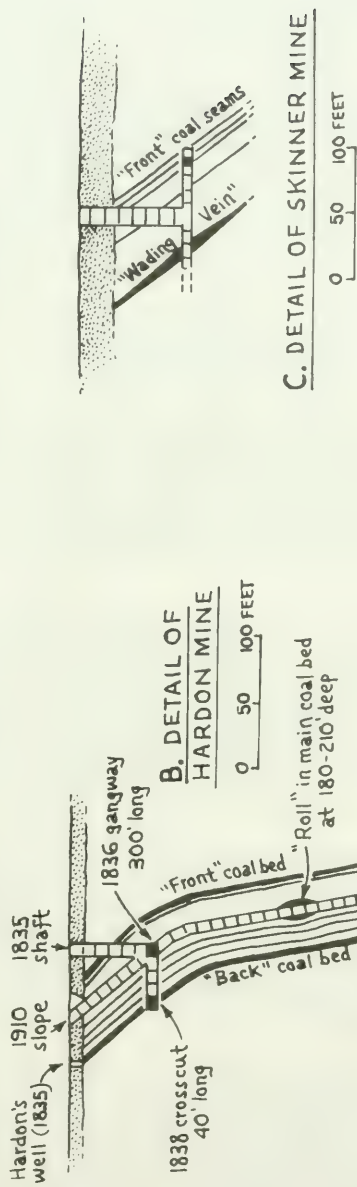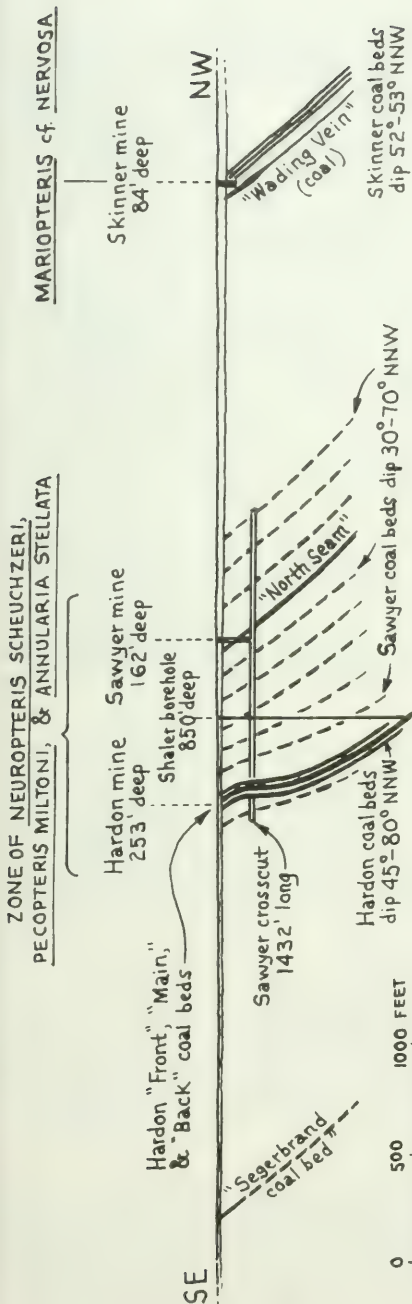
ZONE OF NEUROPTERIS SCHEUCHZERI, PECOPTERIS MILTONI, & ANNULARIA STELLATA

MARIOPTERIS cf. NERVOSA

A. WEST MANSFIELD COAL SECTION

B. DETAIL OF HARDON MINE

C. DETAIL OF SKINNER MINE

FIG. 5

SECTION THROUGH WEST MANSFIELD COAL BEDS

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(Fig. 5A) was reported (Anna H. Segerbrand, Mansfield, verbal commun. to H. B. Chase, 1961) to have been found in an excavation, but was not worked. It probably lies at or near the base of the Mansfield coal sequence, about 1500 stratigraphic feet below the Hardon beds. The 4 or 5 Skinner coal seams lie about 1300 stratigraphic feet above the highest Sawyer beds.

The fixed carbon content of Mansfield coal (based on 11 proximate analyses) averages 95% on a dry, ash-free basis, and the volatile matter averages 5%. The ash content averages 20% on a dry basis. Sulfur content is low, averaging 0.4% to 0.5%. The run-of-mine coal has an average heating value of 10,786 BTU, approximately 80% that of Pennsylvania anthracite (Woodworth, 1899, pp. 190-191; Chute, 1942, p. 17; Sacks, 1975, pp. 3-4). The better coal samples are dark gray to black, very lustrous and cohesive, with a blocky fracture. The average specific gravity of nine of the better samples is 1.71, compared to 1.47 for Pennsylvania anthracite. However, the typical coal is gray, dull to lustrous, platy, fractured, and friable; sometimes slicken-sided or graphitic. It contains up to 40% ash, mainly due to quartz and other impurities, and has a specific gravity of 1.8 to 2.0. The degree of metamorphism increases with the depth of the coal seams (Woodworth, 1899, p. 191).

Most of the coal beds are lenses and could not be traced, at that time, more than a few hundred feet. The thicknesses are extremely variable, ranging up to 20 ft. The Sawyer North Seam (Fig. 5A) in a short distance pinched from about 7 ft to 1-inch thick. The Skinner Wading Vein (Fig. 5C) was said to be 7 to 10 ft thick, but was quickly mined out. A "roll" of coal 19 to 20 ft thick was struck in the Hardon slope (Fig. 5B), but the main Hardon bed averaged only 1 to 3 ft thick.

Jackson (1840) reported 14 species of plant fossils at the Mansfield mines and illustrated Alethopteris serlii, Annularia stellata, Cordaites principalis, Neuropteris scheuchzeri, and Stigmaria. Hitchcock (1841) re-ported Pecopteris, Sphenopteris, and Stigmaria at the Hardon mine, and illus-trated A. stellata, Asterophyllites equisetiformis, Calamites, C. principalis, N. scheuchzeri, Sphenophyllum emarginatum, and several other species from Mansfield.

Lyell visited the mines in 1842 (Lyell, 1845, p. 247). A Boston horticulturist, J. E. Teschemacher (1846), named, described and illustrated about 19 species from the Mansfield mines, some of which Woodworth (1899, p. 191) felt were "of doubtful identification." Lesquereux (Providence Franklin Soc., 1887) described Pseudocopteris irregularis, Rhacophyllum, and Sphenopteris salisburyi from Mansfield. In the 1930's Darrah (1970) collected fossils at Mansfield.

A collection of several hundred fossils from the Mansfield mines, particularly the Hardon, was made by us and Clifford G. Grant in 1974-5; William O. Hocking, Jr., and Allan Pillsbury helped to collect on occasions. About 24 species were recognized (see Table 1). Beautiful specimens of N. scheuchzeri (Fig. 4C), Sphenophyllum cuneifolium (Fig. 4E), and A. stellata (Fig. 4H) and other species (Fig. 4D, F, G; Table 1) were recovered at the Hardon mine site. N. scheuchzeri and C. principalis constitute about two-thirds of the Hardon specimens. A study of these fossils indicates that the West Mansfield coal horizons belong to the Lower Allegheny subseries, corresponding to Lower Westphalian C of Western Europe and Maritime Canada.

Masslite quarry, Plainville, MA. We will eat lunch here. Please
         do not climb quarry walls.

         This area is of considerable interest because it is the only active
coal mining site in the Narragansett basin and also because it is an exceptional
place to study the coal stratigraphy, paleobotany, and structure of the Rhode
Island Formation. About six coal beds or horizons are known from this general
area of Plainville. Beautiful plant fossils of Alleghenian age have been
collected at the quarry (Fig. 4I-P).

         George E. Smith of Norfolk, MA, opened the quarry in 1934 on the
site of an 1885 coal prospect (Fig. 6). Between then and 1945, 440,000 tons
of shale and "slate" were mined for use in the manufacture of roofing granules
by Bird and Son. The coal stratigraphy and structure of the quarry were
previously investigated by Prof. Fred T. Morris of M. I. T. in 1938, by George
E. Smith between 1934 and 1961, and by H. B. Chase in 1961 who prepared a sketch
map of the quarry as it existed at that time.

         During the early 1960's, Dr. John Oleksyshyn of Boston University
with his students (including Lyons) made periodic collections of the fossil
plants exposed in the dark gray shales. Lyons (1969) illustrated
Alethopteris serlii, Annularia sphenophylloides, Eremopteris (now interpreted
as a Sphenopteris species), and a Sphenopteris species (aff. S. barbalata
Bell, 1962). The first extensive report of the fossils of the quarry was made
by Oleksyshyn (1976) who documented 28 species from his collections of the
1960's, including two new species, Palmatopteris narragansettensis and
Palmatopteris plainvillensis. Some of the most important species, reported by
Dr. Oleksyshyn and us, are listed in Table 1.

         The base of the quarry sequence is estimated to be 1000-1500 ft
above the Precambrian basement of Dedham Quartz Monzonite. The sequence of
Pennsylvanian rocks (Fig. 7) as mapped by us in July 1975 consists of medium
gray to dark gray shale, and mudstone interbedded with coal. This unit grades
upward into rusty brown sandstone and then to gray siltstone and fine-grained
sandstone. Northward the coal unit grades into gray fine- to coarse-
grained sandstone with quartzite conglomerate lenses (Fig. 7). The maximum
thickness exposed is 350 ft; three faults interrupt the sequence (Fig. 6).

         The present quarry operation uses a mixture of two parts dark gray
shales and coal to one part siltstone or very fine sandstone to produce a
lightweight aggregate for use in making concrete. The coal is used partly as
an energy source in this process and the product is a clinker-like slab that
is crushed into gravel. This "synthetic" gravel can be seen in a large
conical pile on the left on the way up along the truck road from the parking
lot.

         The structure of the Rhode Island Formation as exposed in the quarry
is illustrated in Fig. 6 and Fig. 7. Three faults were mapped, although others
are obviously present judging by the numerous quartz and occasional calcite
veins mapped in various places in the quarry. The two faults to the south
in the newer pit area of the quarry are NE-trending strike faults that occur
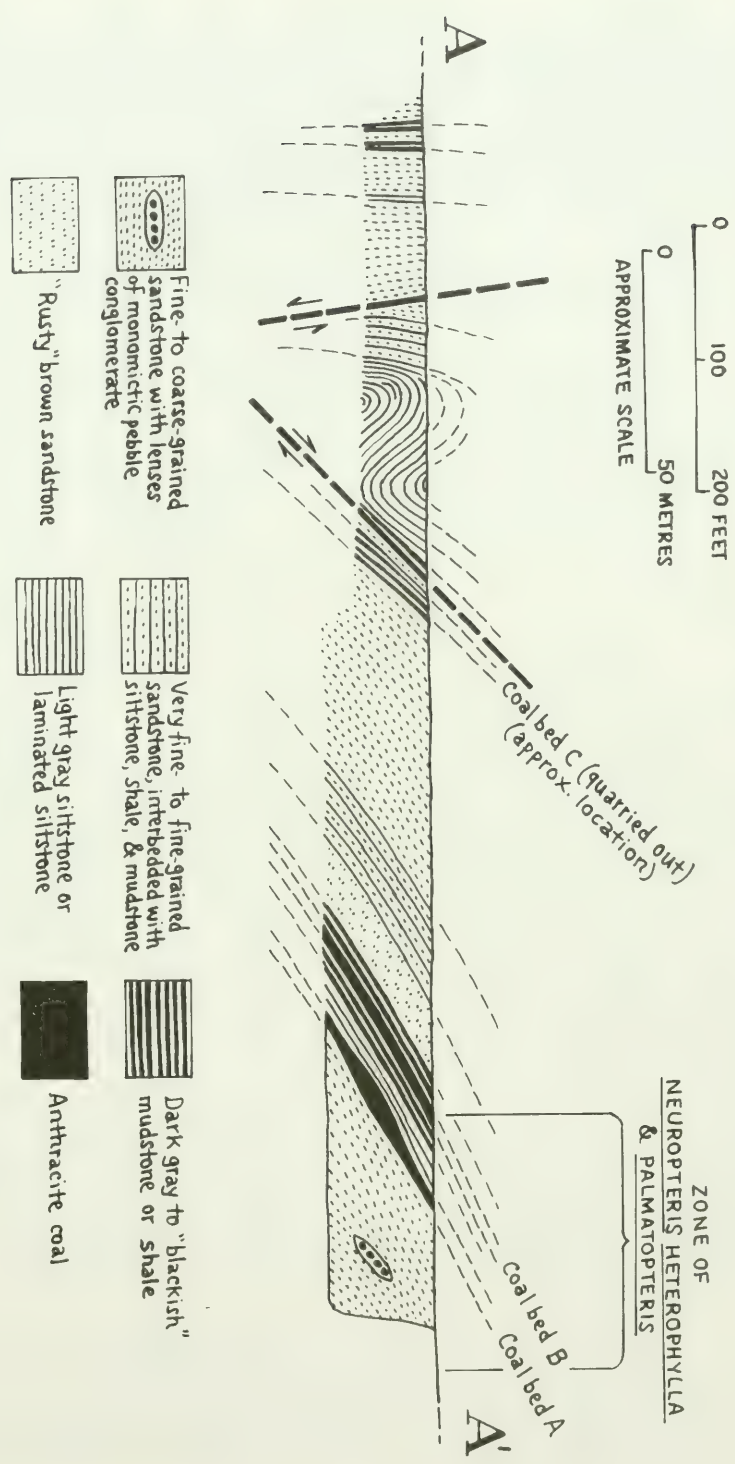on the limbs of a folded horst-like block (Fig. 7). Well-defined non-plunging

FIG. 6

GEOLOGIC MAP OF THE MASSLITE QUARRY,
PLAINVILLE, MASSACHUSETTS

APPROXIMATE SCALE

0   100   200 FEET
0   50 METRES

Fine- to coarse-grained sandstone with lenses of monomictic pebble conglomerate

"Rusty" brown sandstone

Very fine- to fine-grained sandstone, interbedded with siltstone, shale, & mudstone

Light gray siltstone or laminated siltstone

Dark gray to "blackish" mudstone or shale

Anthracite coal

Coal bed C (quarried out) (approx. location)

ZONE OF NEUROPTERIS HETEROPHYLLA & PALMATOPTERIS

Coal bed B
Coal bed A

FIG. 7

SECTION OF RHODE ISLAND FORMATION,
MASSLITE QUARRY, PLAINVILLE, MASSACHUSETTS

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folds can be seen in this block from the north plateau of the quarry. Such folded rocks in this area of Blake Hill were commonly observed by passers-by from Route 1A. The northwestern boundary of the block is evidenced by slickensides, quartz veins, and fault gouge. The southeastern boundary of the block lacks the fault gouge and is a high-angle thrust that has caused the beds in the vicinity of the fault to be upturned into a vertical or near-vertical position and partly overturned on the east side (Fig. 6). The third fault to the north in the older pit area (Fig. 6) is a diagonal fault that is evidenced by slickensides. The strike slip of this fault must be less than 100 ft if our structural interpretation, as given below, is correct. The structure in this area of the quarry and southward to the first strike fault is interpreted to be an asymmetrical anticline plunging 25-30°SSW (Fig. 6).

A 6-ft thick coal bed (Simpson Coal, Woodworth, 1899, p. 182) is probably stratigraphically above coal bed B. Plant fossils were discovered around 1960 by Bernard E. Greene during his cellar excavation on Zeller Avenue in the southern part of the Blake Hill fault block (Fig. 1). These fossiliferous beds would be about 600-700 ft above the southernmost fossiliferous beds west of the diagonal fault (Fig. 6) if a simple model is assumed.

West of the diagonal fault is a sequence of dark gray shale and two exposed coal beds or horizons (Fig. 7). The coal is low-grade, lustrous, "earthy," grayish-black anthracite that is highly fractured, friable, and lacks a conchoidal fracture like most of the anthracite in the Narragansett basin. It is commonly penetrated by numerous quartz veins and veinlets that would give it a high ash content, as indicated by its specific gravity of an average of 1.98. The present exposures of coal bed A, as mapped by us between July and December, 1975, were a measured maximum of 13 ft thick, although the quarry superintendent, Bruce MacDonald (verbal commun., 1975), reported to us that about 100 ft east of the now present easternmost exposure of coal bed A it thickened to 30-35 ft; west of the same exposure it pinched to about 1-2 ft thick; and still further to the west it thickened again to about 13 ft, a total strike distance of about 200 ft. Thus, coal bed A pinches and swells along its strike. He also reported that a stream once followed the strike of this coal, and it can now be seen spilling over the wall of the older pit. In the upper part of coal bed A just below the dark gray shales are small recumbent folds that are interpreted to be drag folds due to strike-slip faulting; numerous closely-spaced quartz veinlets are found in the folded coal. The shale beds in the vicinity of the coal beds appear to be virtually barren of fossils except for an unusual development of Stigmaria (root structures), probably indicating in situ fossil plants (Fig. 6). One Stigmaria mold was found with an abundance of pyrite and unidentified black nonmetallic crystals (?sphalerite) along its cross-section. Pyrite crystals probably oxidized to produce the "limonitic" stains in the beds just below coal bed A and elsewhere in the quarry. Animal fossils are not known with certainty from the quarry, although possible amphibian skin impressions and shell-like masses (?brachiopods) have been observed.

MacDonald (verbal commun., 1975) reported that another coal bed is located about 500 ft south of the newer pit, about 50 ft in front of a power line pole (42°00'43.5"N lat., 71°21'29.4"W long.), buried beneath a thick berm put there as a buffer between the quarry and the residential community. Another coal bed (coal bed C) was reported by MacDonald to have been quarried out; its approximate position is shown in Fig. 7. It was probably stratigraphically above coal bed B.

A systematic attempt by us to collect at the best known fossil localities, F_1 and F_2 (Fig. 6), began in July of 1975. Locality F_1 is a very large quarry block of medium gray shale that was reported by MacDonald (verbal commun., 1975) to have come from just below coal bed A. Exceptional specimens of Neuropteris heterophylla can be collected at F_1 and F_2, as well as other ferns, lycopods, Calamites and its foliage, Cordaites, seeds and cones (Table 1). Cordaites (cf C. principalis) was noted in the broken rock at F_3 and Calamites cistii was found at locality F_4.
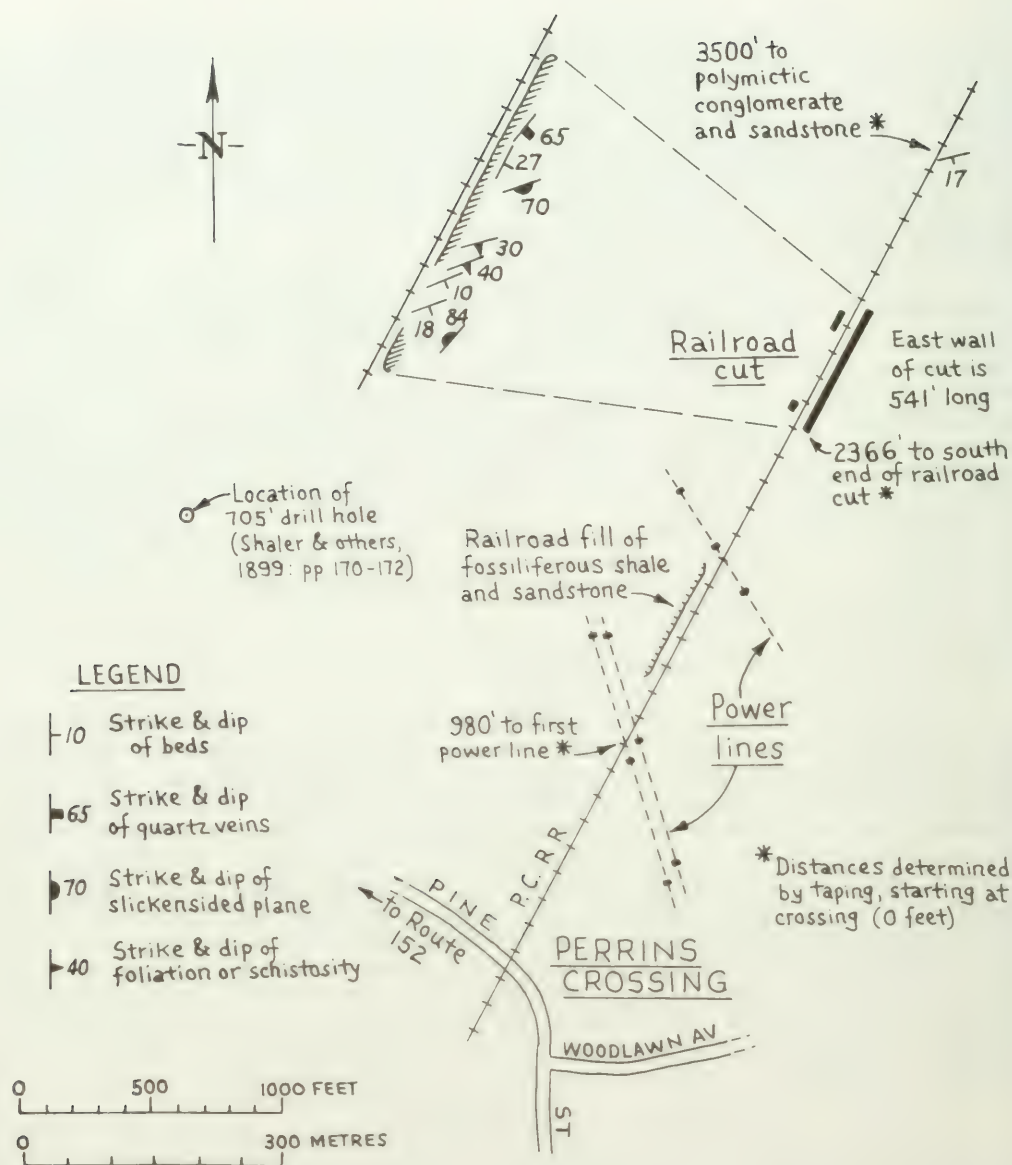
There are a number of sedimentary features of interest in paleo-environmental analysis which can be seen on the quarry walls and on large quarry blocks. Rip-up mudstone clasts with coalified plant stem axes prove local stream erosion and transport. Clusters of plant axes in gray sandstone oriented east-west (Fig. 6) indicate a local westerly paleodrainage, as opposed to the northeastern paleodrainage reported elsewhere in the Narragansett basin by Towe (1959). In the area of fossil locality F_3 (Fig. 6) in rusty brown fine-grained sandstone are bottom markings and load(?) casts. Especially well shown in several places is quartzite pebble conglomerate, a common type of conglomeratic rock found in the Narragansett basin. It was found in situ in one place (Fig. 6); a count of 100 clasts by Lyons indicated 86% quartzite and 14% granitic rocks. Symmetrical ripple(?) marks were observed in the laminated siltstone in the newer pit area.

STOP 4.   Perrins Crossing, Seekonk, Massachusetts

This locality (Fig. 8 and 9) has long been a favorite for collecting Pennsylvanian plant fossils in the Narragansett basin. Woodworth (1899, p. 170) mentioned that Cordaites sp., Pecopteris unita, Odontopteris sp., and a Calamites sp. were exposed in shales in the railroad cut north of Perrins Crossing (Fig. 8). He found "large Pecopteris fronds matted together, but showing the spore cases." Round (1924, 1927) and Darrah (1970) noted about 12 species, notable among which are Pecopteris feminaeformis, Pecopteris polymorpha, Pecopteris hemitelioides, Neuropteris desorii, Alethopteris grandini, and Sphenophyllum oblongifolium, an assemblage indicative of Upper Pennsylvanian. Other species collected by us and Clifford G. Grant of Easton, MA, at the railroad cut and to the south in the railroad fill (Fig. 8) are listed in Table 1. Darrah (1970, p. 38) noted the absence of Neuropteris ovata and Neuropteris scheuchzeri, species typically found in Middle Pennsylvanian beds.

The long railroad cut exposure (Fig. 8) has a stratigraphic thickness of about 100 ft: at the bottom, 35 ft of fine to coarse sandstone with polymictic conglomerate; 45 ft of medium gray metamudstone with fossiliferous shale or slate; and at the top, medium to coarse sandstone with polymictic conglomerate (Fig. 9). The entire sequence exposed along the tracks, including the isolated exposure of polymictic conglomerate and sandstone north of the long railroad cut, is about 200 ft thick and strikes ENE and dips to the SE; foliation is parallel to bedding. One strike fault and two probable NNE-striking diagonal faults, as indicated by quartz veins and slickensides, were mapped (Fig. 8). Noteworthy along the long railroad cut are the fossiliferous horizons, the higher degree of metamorphism indicated by incipient schistosity of the beds, and the presence of large flakes of muscovite and conspicuous grains of biotite. Woodworth (1899, p. 169-170) assigns both exposures to the Perrins anticline, but we did not find the oppositely-dipping beds of the other limb.

3500' to polymictic conglomerate and sandstone *

Railroad cut

East wall of cut is 541' long

2366' to south end of railroad cut *

Location of 705' drill hole (Shaler & others, 1899: pp 170-172)

Railroad fill of fossiliferous shale and sandstone

980' to first power line *

Power lines

* Distances determined by taping, starting at crossing (0 feet)

LEGEND

⊢10   Strike & dip of beds

⊢65   Strike & dip of quartz veins

▶70   Strike & dip of slickensided plane

⊢40   Strike & dip of foliation or schistosity

PINE

P.C. R.R

to Route 152

PERRINS CROSSING

WOODLAWN AV

ST

0 ___ 500 ___ 1000 FEET

0 ___ 300 METRES
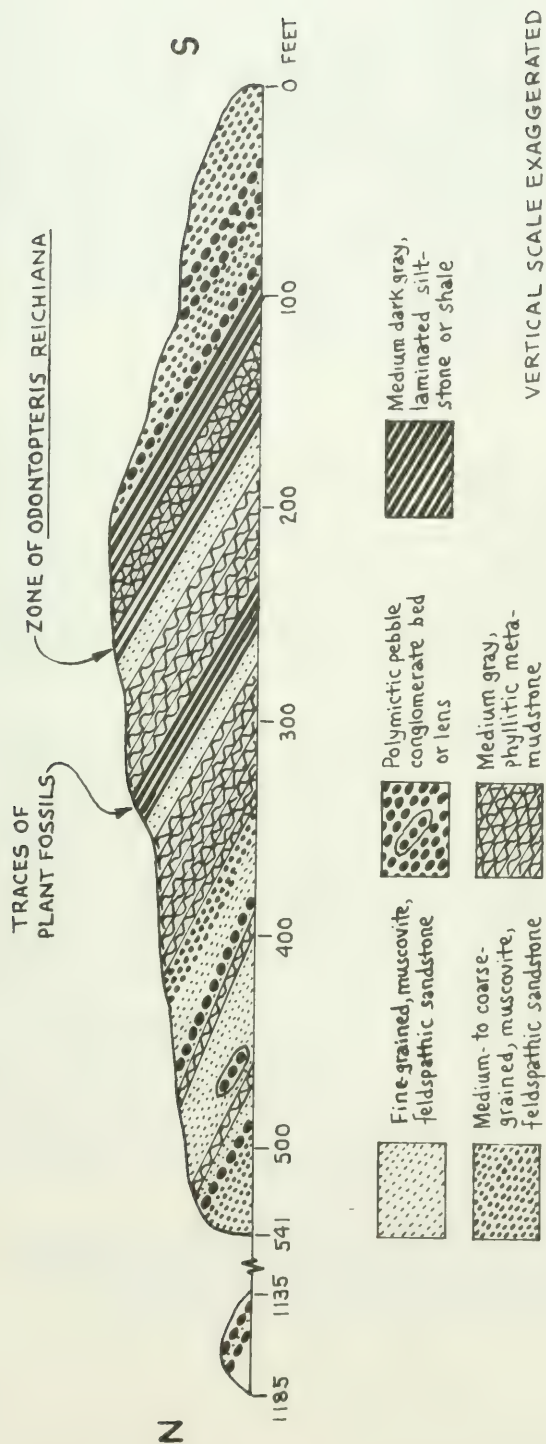
FIG 8

GEOLOGIC MAP OF AREA NORTH OF PERRINS CROSSING, SEEKONK, MASSACHUSETTS

FIG. 9

UPPER PENNSYLVANIAN BEDS
OF RHODE ISLAND FORMATION
NORTH OF PERRINS CROSSING,
SEEKONK, MASSACHUSETTS

Fine-grained, muscovite, feldspathic sandstone

Medium- to coarse-grained, muscovite, feldspathic sandstone

Polymictic pebble conglomerate bed or lens

Medium gray, phyllitic meta-mudstone

Medium dark gray, laminated silt-stone or shale

VERTICAL SCALE EXAGGERATED

ZONE OF ODONTOPTERIS REICHIANA

TRACES OF PLANT FOSSILS

S

0 FEET

100

200

300

400

500

541

1135

1185

N

Of considerable importance in this area, about a half-mile west of
the railroad cut (Fig. 8), is a boring that penetrated an estimated 625 strati-
graphic feet in the assumed middle section of the Rhode Island Formation
(Woodworth, 1899, p. 170-173). Thirteen coal horizons, with coal seams up to
about 2 ft thick, not including an alleged fraudulent anthracite coal bed re-
corded near the bottom of the hole, were noted. The coal almost always occurs
in "slate" and is commonly associated with "impressions of coal plants," noted
13 times throughout the entire thickness of the boring. The coal sequence be-
gins at about 70 stratigraphic ft above the base of the core sequence and is
estimated to be 330 stratigraphic ft in thickness. The top of the borehole
sequence was considered by Woodworth (1899, p. 170) to underlie the shale
section (presumably our metamudstone unit, Fig. 9) along the railroad tracks.
Near the top of the coal sequence is red conglomerate which was not correlated
by Woodworth (1899, p. 172-173) with the Wamsutta Formation. He also noted
(p. 173) a red slate core with annelid casts from this boring. This coal se-
quence is almost certainly younger than those found at West Mansfield and
Foxborough (Fig. 3, Fig. 5).

STOP 5. Thacher Street, Attleboro, Massachusetts. No hammer outcrop.

Although plant fossils or coal beds are not known from this exposure,
the unusual and especially well displayed features merit investigation. This
NE-striking vertical sequence of the Rhode Island Formation (Quinn, 1963, p.
10) is about 200 stratigraphic ft thick and consists, from bottom to top, of
80 ft of gray thickly-bedded sandstone interbedded with or including lenses
or channel fillings of polymictic pebble conglomerate, and 120 ft of gray
fine- to medium-grained, cross-bedded sandstone including 50 ft of gray fine-
to medium-grained sandstone thinly bedded with red or grayish red siltstone
and thicker beds of polymictic pebble conglomerate (Fig. 10).

Glacial polishing has magnificently revealed the fine structures of
the beds. Noted were cross-bedding and graded bedding, minute clastic dikes
associated with small-scale slump structures, and channel fillings (Fig. 10)
(see also Mutch, 1963, Fig. B-2; Mutch, 1968, Pls. 1-3). Woodworth (1899,
p. 176) noted that a disconformity occurs between the red beds and the overlying
gray sandstone and the presence of residual coarse pebbly beds (Fig. 10). Mutch
(1963, p. 20) mentions that mottling in the sandstone and siltstone may indicate
reworking by burrowing animals. The Thacher rocks show a lower degree of meta-
morphism compared to rocks further south in the Narragansett basin (Quinn, 1963,
p. 10).

The stratigraphic position of the Thacher beds with respect to the
Perrins beds indicates that the former are higher up in the section (Woodworth,
1899, p. 176) and thus probably also Late Pennsylvanian. The presence of red
beds this high up in the section points to caution in using the term "Wamsutta
Formation," a red bed sequence exposed northward in the type locality at North
Attleboro (Fig. 1) and of known Alleghenian age (Knox, 1944), for red beds in
the Narragansett basin.

The glacial features of the exposure are superb by themselves. Glacial
striae, grooves, and plucking at the southern end of the exposure (Fig. 10)
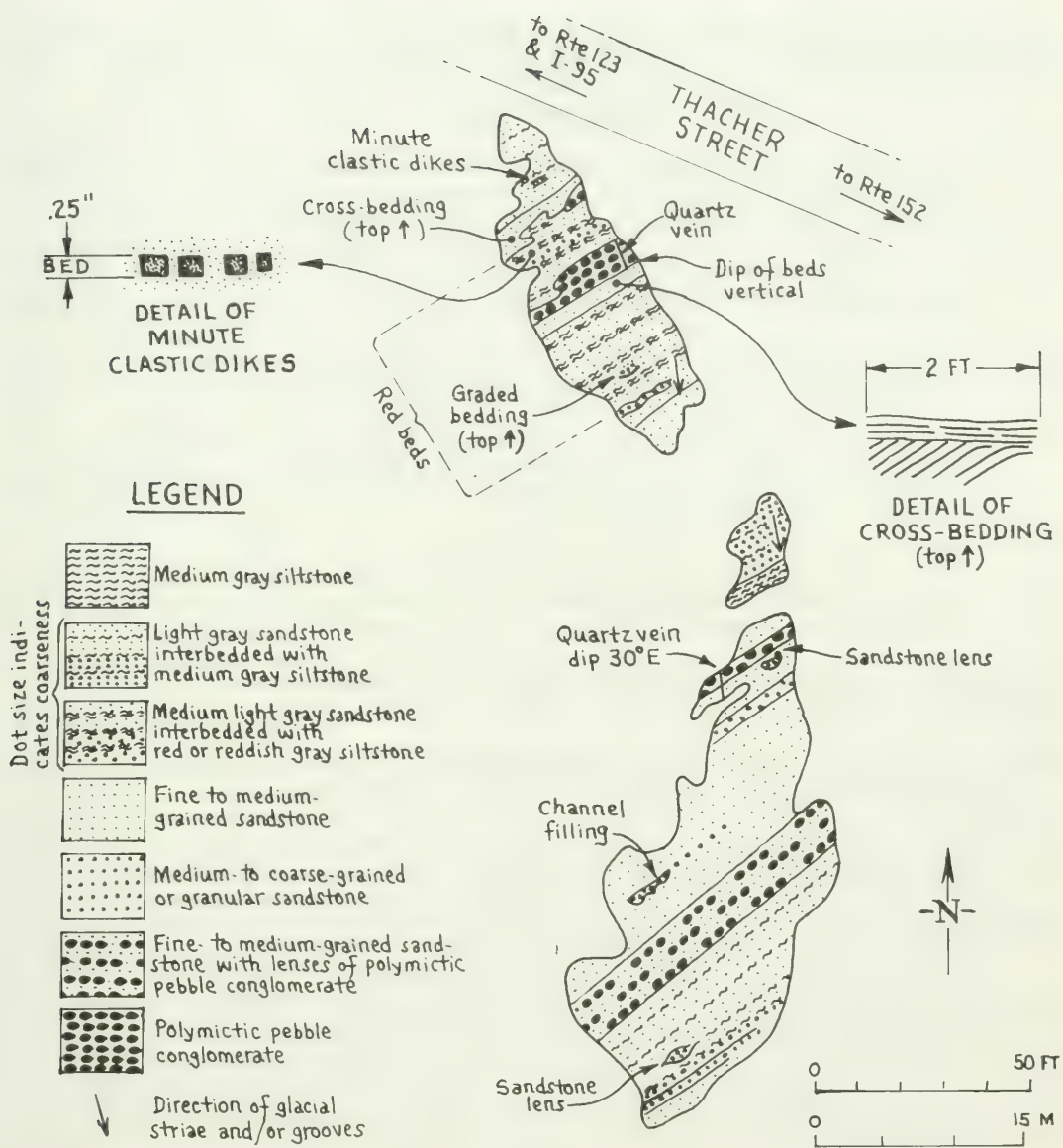
to Rte 123 & I-95

to Rte 152

THACHER STREET

Minute clastic dikes

Cross-bedding (top ↑)

Quartz vein

Dip of beds vertical

.25"

BED

DETAIL OF MINUTE CLASTIC DIKES

Red beds

Graded bedding (top ↑)

2 FT

DETAIL OF CROSS-BEDDING (top ↑)

LEGEND

Dot size indicates coarseness

Medium gray siltstone

Light gray sandstone interbedded with medium gray siltstone

Medium light gray sandstone interbedded with red or reddish gray siltstone

Fine to medium-grained sandstone

Medium to coarse-grained or granular sandstone

Fine to medium-grained sandstone with lenses of polymictic pebble conglomerate

Polymictic pebble conglomerate

Direction of glacial striae and/or grooves

Quartz vein dip 30° E

Sandstone lens

Channel filling

-N-

Sandstone lens

0   50 FT

0   15 M

FIG. 10

MAP OF VERTICAL BEDS
OF RHODE ISLAND FORMATION,
THACHER STREET, ATTLEBORO, MASSACHUSETTS

indicate that a Pleistocene glacier moved S10°E. In the southern part of the
exposure there is evidence of stream erosion related to glaciation (Mutch, 1963).

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Log Starting from Route 140 Southbound at I-95 Overpass

Mileage
  Cum.

0.0   Route 140 southbound at intersection with I-95. STOP 1.

1.2   Route 106, continue on Route 140.

1.6   Railroad bridge. Coal bed exposed here in 1955 during building of underpass. Fern fossils also observed.

1.8   Straight ahead to School Street.

3.4   Turn right at white posts onto Old Elm Street.

3.6   Stop at Stadtwald Kennel Sign. Old Hardon Mine shaft, now filled in, is located about 100 ft north of street. STOP 2.

3.8   Bear left at Purdy's corner, continue on Old Elm Street.

4.1   Turn left onto School Street.

6.0   Intersection with West Street, continue along Route 140.

6.6   Left on Route 106. Continue west on Route 106 to Plainville Center.

7.7   I-95 overpass.

8.5   Route 495 underpass.

11.1   Intersection with Route 152. Continue along Route 106.

12.0   Intersection with Route 1. Continue along Route 106 to Plainville Center.

12.7   Plainville Center. Right turn onto Route 1A.

13.5   Rhode Island Formation on right. Beds here strike NNE.

14.5   Turn left on Green Street (note Masslite sign). If bridge is closed, return to Route 1A, turn right and take right on Cross St. Follow signs to Masslite quarry.

14.7   Turn left on Wentworth Street.

15.3   Turn left at Cross Street (no street sign).

15.5   Turn right on road leading to Masslite quarry.

Mileage
Cum.

15.8   Masslite quarry. Park in parking lot. Walk southwest along road
        leading up to quarry. STOP 3.

15.8   Return along quarry road.

16.1   Bear left on to Cross Street.

16.4   Turn right.

16.9   Turn right on Green Street.

17.1   Turn right on Route 1A.

18.9   Turn left on Route 106 at Plainville Center.

19.6   Cross Route 1.

20.5   Turn right on Route 152 to Seekonk, Mass.

21.8   Route I-95 underpass.

25.7   Attleboro Square. Continue on Route 152.

27.0   Railroad bridge.

28.4   Hebronville Railroad Bridge (East Junction).

28.7   Attleboro-Seekonk town line.

29.7   Turn left on Pine Street.

30.2   Perrins Crossing. STOP 4. Walk north along tracks to railroad fill
        and then to railroad cut (see Fig. 8).

30.3   Turn around at GM Industries, Inc. and return to Route 152 along
        Pine Street.

30.4   Perrins Crossing.

30.9   Turn right onto Route 152.

33.6   Railroad bridge again.

34.5   Left on Thacher Street (Look for "Fast Car Wash" sign).

35.0   Bear left over bridge and park on right. STOP 5.

35.0   Continue on Thacher Street.

35.5   Intersection. Continue straight on Route 123.

36.4   Turn right on ramp leading to Interstate 95, northbound. Return to
        Boston.

PRE-PENNSYLVANIAN ROCKS OF AQUIDNECK AND

CONANICUT ISLANDS, RHODE ISLAND

by

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Introduction

Approximately four square miles of pre-Pennsylvanian rocks crop out on Sachuest Point and at Newport Neck on Aquidneck Island and on the southern half of the eastern part of Conanicut Island in Rhode Island. These rocks have received only sporadic attention since the late 1800's and early 1900's. They are an important group of rocks in that they represent a period of time that is not well understood in the geologic history of southern New England. The presence of carbonate rocks in the section separates them from the Pennsylvanian and has caused earlier workers to suggest correlations with the Cambrian rocks in the Boston Basin (Crosby, 1897; Foerste, in Shaler, Woodsworth and Foerste, 1899), or with the Precambrian(?) Blackstone Series in Rhode Island. The porphyritic granite that intrudes the pre-Pennsylvanian volcanic rocks does not resemble granites on the western side of Narragansett Bay (Quinn, 1971). Age dating on zircons from the granite, presently in progress, should aid in correlation. The purpose of this trip is to examine the relationship of the Pennsylvanian and pre-Pennsylvanian rocks, to look at the range of lithologies present in the pre-Pennsylvanian rocks, and to look at the deformation of the pre-Pennsylvanian rocks.

Relationships of Pre-Pennsylvanian and Pennsylvanian Rocks

The relationship between the pre-Pennsylvanian and Pennsylvanian rocks is clearly exhibited on the west side of Conanicut Island (STOP 1) where the pre-Pennsylvanian granite lies unconformably beneath arkoses in the Pennsylvanian Pondville member of the Rhode Island Formation. These arkoses were apparently derived from weathering of the granite during Pennsylvanian times (Pirsson, 1897).

Pre-Pennsylvanian Rock Units

a. Introduction: Rock Types and Metamorphism.--The pre-Pennsylvanian rocks have traditionally been mapped as three units: a porphyritic granite, a volcanic unit consisting of volcanic flows and volcaniclastic sediments with some nonvolcaniclastic sediments, and a sedimentary unit consisting of

nonvolcaniclastic sediments. The granite is intrusive into the volcanic units on Cliffwalk (STOP 2) and aplite and pegmatite dikes cut the volcanic rocks in other areas. The sediment and volcanic units are separated by an unexposed fault which runs from Prices Neck to Brenton Cove. Neither the relationship between the units or the nature of the fault is apparent. The distribution of the rocks on Newport Neck and the location of Stops 2-7 are shown on the map in Figure 1. The rocks on Conanicut Island consist of granites in contact with the volcanic unit. The rocks at Sachuest Point are in the volcanic unit (STOP 8).

The pre-Pennsylvanian rocks in the area have undergone a regional metamorphism in the lower greenschist facies (chlorite zone) during late Pennsylvanian or early Permian times (Quinn, 1971). Preliminary petrographic examination of metamorphic assemblages in these rocks seems to support this contention. The preservation of primary sedimentary volcanic features such as accretionary lapilli suggest that these rocks have never been at very high metamorphic grade.

b. Porphyritic Granite.--The major phase of the granite is well exposed along Cliffwalk (STOP 2). It is a porphyry containing large pink phenocrysts of microcline which may be several inches across. Other major phases include quartz, albite or oligoclase, biotite and locally hornblende. The mafic phases are generally altered to chlorite. An analysis of this rock is given in Table 1. In other areas, for example along the west side of Lily Pond on Newport Neck and at the road cut just west of Bailey Beach, the microcline phenocrysts are much smaller and the mafic minerals are minor modally. Often the albite in

TABLE 1. Analyses of the Newport Granite

	A-1	B-2	D-4
SiO_2	75.60	74.34	71.23
TiO_2	.06	.17	.21
Al_2O_3	13.32	13.67	13.64
Fe_2O_3*	.80	1.13	1.70
FeO	--	–	–
MnO	.08	.10	.05
MgO	.03	.11	.75
CaO	.36	.68	2.31
Na_2O	4.73	3.88	3.55
K_2O	4.08	4.87	3.79
L.O.I.	.65	.82	1.72 (H_2O)
TOTAL	99.71	99.77	99.95

A-1 - Aplitic phase of the granite from roadcut on Ocean Drive at Hazard Beach
B-2 - Medium grained phase of the granite from roacut on Ocean Drive west of Bailey Beach
A-1 and B-2 are XRF analyses using USGS G-1 and GSP-1 as standards
D-4 - Porphyry granite from Conanicut Island wet chemical analyses (Pirsson, 1893)
* Total Fe as Fe_2O_3

Figure 1. Geologic Map of Newport Neck, Rhode Island, showing
           STOPS 2-7.

Partly taken from map by George E. Moore, Jr., and Samuel J. Pollack, compiled
by A. W. Quinn, in Mutch (1963a).

Base from Newport 7.5 minute topographic sheet. The contour interval is ten
feet. Datum is mean sea level. Approximate mean declination is 14-1/2°.
1957.

Explanation

        Pennsylvanian: Pri - Rhode Island Formation

        Pre-Pennsylvanian: pg - porphyritic granite
                              sv - volcanic unit
                              s - sediment unit

        contact   _____   _ _ _ _ _
                              established   inferred

        fault   _____   _ _ ......
                              established   inferred

        strike and dip of bedding - $\prec\!\!\prec^{17}$

        strike and dip of overturned bedding - $\overset{65}{\prec\!\!\prec}$

        strike and dip of foliation - $\prec\!\!\prec^{16}$

        strike and dip of second foliation - $\prec\!\!\prec^{18}$

        bearing and plunge of lineation - $\longrightarrow^{9}$

        parking - pkg ■

        STOP locality 5

Figure 1

these rocks is green in color. A chemical analysis of this granite is given in column 2 of Table 1. The granite is cut by quartz, pegmatite, and abundant aplite dikes. An aplitic phase of the granite forms a large portion of the hill west of Lily Pond and a septum of volcanic rocks separates the aplite from the main granite. The aplite crops out in a road cut on the north side of Ocean Drive at Hazard Beach. An analysis of this aplite is given in column 1 of Table 1. The analyses of the Newport granite indicate that it is a true granite (minimum melt composition). Inclusions are uncommon, although rounded xenoliths five to six inches across, which resemble the volcanic unit in hand specimen, have occasionally been found. Shear zones resulting from the deformation are frequently observed in outcrop. In thin section, the quartz and the feldspars are badly deformed and shear zones can be seen on the scale of the thin section.

   c. The Volcanic Unit.--The volcanic unit consists of volcanic conglomerate, sandstones and siltstones of probable volcanic origin, lapilli tuffs, and occasional flows. Most of the rocks are dense, grey-green, fine-grained flinty rocks which appear featureless in the field. In thin section, many are fine-grained aggregates of quartz, feldspar, chlorite, sericite, and magnetite and probably are tuffaceous siltstones of acidic volcanic origin. Others are sandstones composed of subangular to subrounded quartz grains, twinned feldspars, with various amounts of finer-grained matrix similar in composition to the siltstones. Microcline grains have been found in a few of the sandstones. These sandstones are also probably tuffaceous and largely derived from acidic volcanic debris. The volcanic conglomerates are distinctive in the field and are composed of pebbles of volcanic rocks of various compositions, as well as some volcaniclastic sediments, quartzite, and chert pebbles. Quinn (1971) reports that some pebbles of granite have been found in the conglomerates. Distinctive red jasper pebbles have been found in the conglomerates around Brenton Cove. Accretionary lapilli tuffs have been found at the locality at STOP 6, and probable accretionary lapilli have been found in several other localities. The presence of accretionary lapilli suggests that a volcanic vent was several miles away (Moore & Peck, 1962). The only rocks so far examined which seem to actually represent flows (e.g. some of the rock intruded by granite at Cliff-walk) were probably basaltic andesite to andesite in composition based on euhedral pyroxene outlines of phenocryst and the presence of some quartz. Because of the metamorphism, these rocks are now principally composed of albite-chlorite-actinolite-iron oxide and minor quartz.

   d. The Sedimentary Unit.--The sediments which are exposed in the western end of Newport Neck and on Goat Island consist primarily of sandstones, slates and siltstones, with minor carbonates, conglomerates, and fairly clean quartz arenites. An andesite dike cutting the sediments can be seen in at least one locality (STOP 4). Rocks of basic igneous origin can be seen interlayered with the sediments.

The sandstones are greenish grey, grading to light grey and reddish grey in color. In many places they exhibit graded bed relations with the slates and tops of beds are clearly indicated. The sandstones are interlayered with slates and siltstones in some localities. Petrographically, the sandstones are graywacke in type. They contain fragments of slate, quartzite, chert, volcanic rocks, and grains of twinned feldspars, quartz, clinozoisite and some altered mafic minerals. Gneissic fragments and metamorphic minerals such as

garnet have not been found. All of the feldspar is albite and the matrix is chlorite, sericite, quartz, with some iron oxide and epidote.

The purplish slates and light grey siltstones are interbedded with the sandstone. A thick sequence of purplish slates interbedded with some green slates can be seen in the southern part of the western side of Newport Neck along Ocean Drive. The slates consist largely of sericite, chlorite, fine-grained quartz, and opaques. Carbonaceous greenish-grey slates in one horizon about 25 feet thick on the west side of Castle Hill (STOP 4) contain large elliptical concretions of carbonate and quartz. The siltstones are comprised primarily of very minute grains of quartz with some sericite and feldspar. They are of ambiguous origin since they have been metamorphosed, but may have originally been cherts or ash layers.

Minor conglomerates occur in the sediment section. A conglomerate associated with carbonate-containing shales near Graves Point (STOP 3) contains rounded pebbles of limestone. Conglomerates associated with sandstones, shales, carbonates and quartzites at Fort Adams (STOP 5) contain pebbles of both sedimentary and volcanic origin.

Good carbonate rocks can be found at Ida Lewis Rocks and in five localities around Brenton Cove. The carbonates at Ida Lewis Rocks (STOP 7) are massive, light grey to blue grey dolomites with minor pinkish dolomites. Pinkish to grey dolomite around Brenton Cove is interbedded with purple and green slates, sandstones, and quartzites. Talc and serpentine are associated with the carbonates in some localities. Thin carbonate layers have been reported on the west side of Castle Hill by Dale (1884). Fossils have not been found in carbonate rocks anywhere in the pre-Pennsylvanian.

Red jasper pebbles similar to those found in the volcanic conglomerates have been found in sandstones at a number of localities on the north end of Newport Neck, particularly around Brenton Cove.

    e. Discussion of the Relationship Between the Volcanic and Sedimentary Unit.--The relationship of the volcanic unit and the sedimentary unit is not obvious in any of the localities examined in this study or in any of the localities studied by earlier workers (Dale, 1884; Shaler, Woodworth and Foerste, 1899; and Quinn, 1971). Quinn (1971) states that the general lithologic and structural characters suggest that the slates and quartzites of the sedimentary unit grade upwards into the volcanic unit. The presence of red jaspers in the sandstones, slate and carbonate sequence, as well as in the volcanic conglomerate around Brenton Cove, support Quinn's statement suggesting that these units were deposited continuously, and that there is no major break in time between the volcanic and sedimentary units at this locality. The presence of volcanic fragments in the conglomerates in the sedimentary sequence at Brenton Cove and the presence of quartzite in the volcanic conglomerate suggest a mixed volcanic and sedimentary source area for both units. Fragments of volcanic rocks in the graywacke sequence suggest that the sedimentary unit exposed along Ocean Drive was at least partially derived from a volcanic terrain. The presence of andesite dikes in the sedimentary unit suggest that volcanic activity was occurring in the area during or after the deposition of part of the sedimentary unit. It seems possible that the sedimentary and volcanic units represent two environments that were roughly contemporaneous, the two now being

displaced along faults and not necessarily spatially arranged as when they were deposited. Minor faults and movement on joints are very evident in coastal outcrops and probably more faults exist than have been mapped. Construction of a detailed time-stratigraphic sequence and paleogeographic map of these rocks is difficult because of displacements along faults, complex deformation, and rapid facies changes in the units themselves.
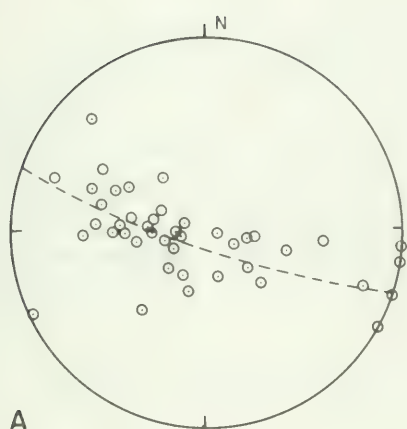
Structure

Pennsylvanian rocks in the Narrangansett Basin have strongly developed north to northeast trending structures associated with a late Pennsylvanian-early Permian deformation. Stereographic projections of poles to bedding, poles to cleavage, and lineations for the Pennsylvanian rocks in the Narrangansett Basin from Quinn's (1971) map are shown in Figures 2A, 2C and 2E, respectively. Pennsylvanian structures shown in Quinn's map in the southern Narragansett Basin show a particularly pronounced north-south orientation. North-south trending structural features are also developed in the pre-Pennsylvanian sediments along Ocean Drive (see Figure 1). Stereographic projections for poles to bedding, poles to cleavage and lineations are shown in Figures 2B, 2D and 2F. Two cleavages are recognized, but are difficult to correlate from outcrop to outcrop, in both the Pennsylvanian and pre-Pennsylvanian rocks. Therefore, in the stereographic projections, the two cleavages are not differentiated. The stereographic projections for the pre-Pennsylvanian rocks, as well as the structural measurements on the map in Figure 1, indicate that an east-west, as well as a north-south, structural trend is present in the pre-Pennsylvanian rocks. This east-west trend is best illustrated by the east-west strike of bedding in the volcanic unit and by east-west cleavage-bedding intersections in the sediments on Ocean Drive. The presence of these east-west structures in the pre-Pennsylvanian rocks may indicate a pre-Pennsylvanian deformation. However, east-west structures may be present in the Pennsylvanian rocks and not be known to the authors, or they may not have been recognized because they are subordinate to the north-south structures. Until more data on the Pennsylvanian become available, the suggestion of a pre-Pennsylvanian deformation is speculative. An angular unconformity between the Pennsylvanian and the pre-Pennsylvanian rocks at Sachuest Point may support a pre-Pennsylvanian structural event.
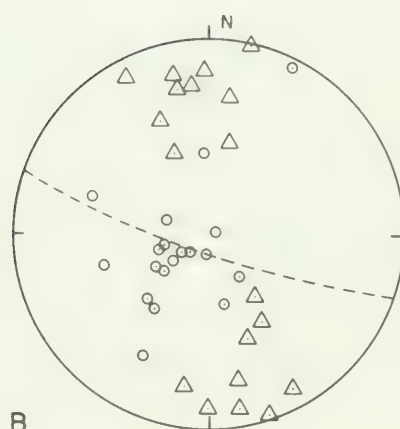
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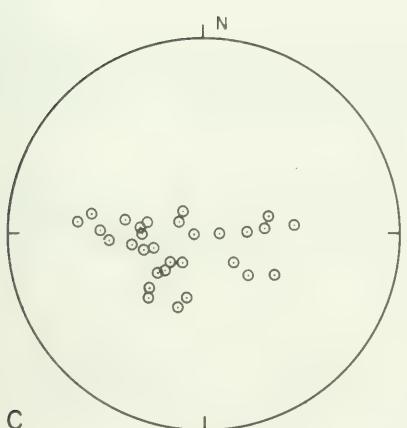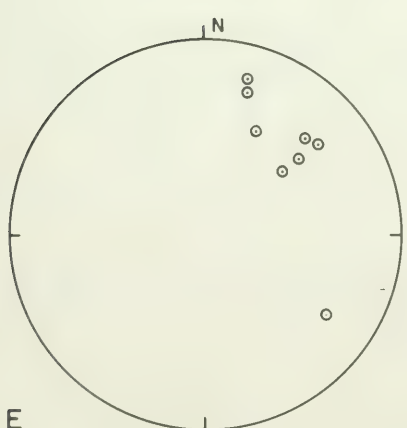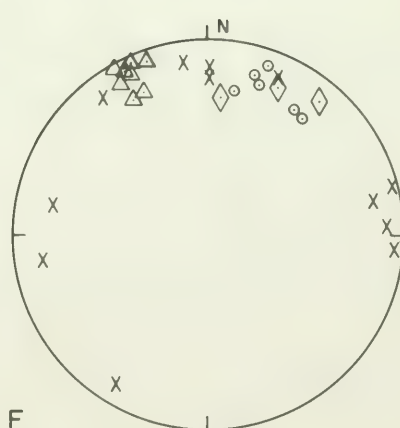
Figure 2

Figure 2.   Comparison of structural measurements in Pennsylvanian
            Rhode Island Formation versus pre-Pennsylvanian rocks
            in the Narragansett Basin.

A. Poles to bedding of Pennsylvanian rocks (Quinn, 1971).

B. Poles to bedding of pre-Pennsylvanian rocks. Circles are the sedimentary
    unit, triangles are the volcanic unit (some of these measurements may be
    cleavages). Note the N-S girdle indicating east-west striking beds in the
    volcanic unit that is not present in A.

C. Poles to cleavage of Pennsylvanian rocks (Quinn, 1971).

D. Poles to cleavages of pre-Pennsylvanian rocks.

E. Pennsylvanian lineations--nature of these lineations not reported
    (Quinn, 1971).

F. pre-Pennsylvanian lineations. Circles are intersection of two cleavages,
    X's are intersections of cleavage and bedding, triangles are fracture and
    mineral lineations, diamonds are fold axis (approximate). Note the E-W
    cleavage-bedding intersections not present in E.

Measurements on pre-Pennsylvanian rocks are mainly by the author. A few
measurements, particularly bedding dips in the volcanics, are from the map
compiled by Quinn, in Mutch (1963). Measurements were plotted on an equal
angle stereonet.

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Road Log

Road Log

Map Coverage

Topographic Maps

Narragansett Pier, 7.5 minute, STOP 1.
Newport, 7.5 minute, STOPS 2-7.
Sakonnet Point, 7.5 minute, STOP 8.

Geologic Maps

Bedrock Geologic Map of Rhode Island, in Quinn (1971).
Sketch Geologic Maps in Figures B-1, B-4, B-10, in Trip B, and in
    Figure E-2, Trip E, by T. A. Mutch, NEIGC 1963 Guidebook.

Itinerary

About 13 mi. S. of Providence on I-95 exit left (exit 9) on R. I. R.
Proceed on R. I. 4. through traffic circle at about 6 mi. to the R. I. 138
east exit at 10.3 mi. Exit onto R. I. 138 and cross Jamestown Bridge at
13.3 mi. Road log starts at E. end of bridge.

Mileage

0.0   E. end of Jamestown Bridge.

0.7   Turn right (S.) onto North Main Road.

2.7   Cumberland Farms store on right. Purchase lunch materials if
       necessary.

2.8   Stop sign. Continue straight ahead on Southwest Ave.

3.3   Road bears right. Turn left (E.) onto Hamilton Ave.

3.4   Turn right (S.) onto Highland Dr.

3.8   Bridge. Park after bridge for Stop 1.

STOP 1. Outcrops are along the shore. Obtain permission before crossing private property to reach the shore. Low-lying stretch is mapped as a fault <u>within</u> the Pennsylvanian; grey outcrops to the north are schists of the Rhode Island Fm. Walk south toward the low cliffs. Notice boulders and then low outcrops of distinctive granule conglomerate composed of dark grey quartz grains in a whitish clay-rich matrix. As you continue south this conglomerate grades into arkosic conglomerate, weathered granite, and finally sound granite similar to that exposed at Cliff Walk on Aquidneck Island (Stop 2). The granule conglomerate and the arkosic conglomerate are similar to those found near the base of the Pennsylvanian in other parts of the Narragansett Basin; they are called the Pondville Conglomerate from a type locality at Pondville Station, Massachusetts. These relations and those exposed at Sachuest Point on Aquidneck Island (Stop 8) establish the pre-Pennsylvanian age of the rocks of the Newport area.

Retrace route to stop sign at mileage 2.8.

5.0   Turn right (E.) onto Narragansett Ave.

5.4   Stop sign; ferry landing. Turn left (N.) onto Canonicus Ave. Rexall Drug store on corner sells Newport Bridge tokens for 1.10 (toll is $2.00 without token).

5.8   Bear left on R. I. 138.

6.2   Bear left on R. I. 138 east for Newport via toll bridge.

9.4   Take Downtown (Scenic) Newport exit. Turn right (S.) at stop sign onto Farwell Ave. which becomes Thames St. as you continue S.

10.7   Mainstream traffic bears left onto Bellevue Ave. Stay in right lane through a slight sinistral jog to continue on S. on Thames St. (following signs to Ocean Drive).

11.1   Turn right (W.) onto Wellington Avenue. (Signs "to Ocean Drive".)

11.4   Little League field (Marine Field). Consolidate cars here; we will return to this point after Stop 7. Return to Thames St.

11.6   Stop sign. Turn right (S.) onto Thames St.

11.9   Gulf Station on left. Bear slightly right; Thames St. becomes Carrol Ave.

12.0   "Y" intersection with granite memorial with plague dedicated to Joseph Martin. Bear left on Carrol Ave.

12.2   Stop sign at Ruggles Ave. Continue straight ahead.

12.7   Stop sign. Turn left (E.) onto Ocean drive.

12.8   Crest of hill; intersection with Jeffrey Rd. Outcrops of
            porphyritic granite on both sides of road. Granite A-1 in
            Table 1 is from outcrop on left.

13.2   T-intersection with Coggeshall Ave. Turn right (S.).

13.3   Road turns left and becomes Bellevue Ave.

13.4   Turn right (S.) onto Ledge Rd.

13.6   Leave cars; they will meet us at the end of the Cliff Walk
            traverse of Stop 2. Cliff Walk starts on left (E.) at end
            of street. Road log for the cars to the meeting place
            follows.

13.9   Stop sign. Turn right (E.) onto Bellevue Ave.

14.0   Bellevue Ave. turns left (N.).

14.8   Just north of Rosecliff, turn right (E.) onto unmarked
            road (Marine Ave.) which leads to Cliff Walk.

15.0   End of Marine Ave. at Cliff Walk.

            Stop 2. Pennsylvanian and Pre-Pennsylvanian Rocks Along Cliffwalk
            Park on the west side of the road near Land's End. We will walk
            north around the coast to Maine Avenue near Hatch School where the
            cars will meet us.

            The main phase of the porphyry granite containing abundant large
            pink potassium feldspar phenocrysts is exposed along the coast
            from Land's End to just north of Rough Point. Dikes of aplite,
            quartz, and pegmatite cutting the granite are quite common. A
            few inclusions that look like fragments of the volcanic unit can
            be seen in the granite near the shore. Shearing of the granite
            is evident in many places. Note the good glacial striations
            and polish.

            North of Rough Point, the granite abruptly terminates against
            the green volcanic unit. Except near the low tide mark where
            the granite is in direct contact with the volcanic unit, an
            aplite vein five to six inches thick runs along the contact.
            Locally the aplite deviates to cut both the granite and the vol-
            canics. Near the contact with the granite the volcanic unit has
            a more granular structure than usual. In thin section this rock
            contains altered feldspars and amphiboles and could have originally
            been a mafic to intermediate flow that was metamorphosed by the
            granite. A flow structure can be seen in the volcanic unit near
            the contact. Dikes, sills, and blebs of granite material pri-
            marily aplite cut the volcanic unit along the coast both near
            and away from the contact.

The rocks from just north of Rough Point to Sheep Point are typical
of rocks in the volcanic unit and are primarily sandstones and
siltstones. Occasional conglomeratic layers are also found.

An E-W trending fault passes through the covered stretch between Sheep
Point and the dark grey outcrops on which the pagoda is built. This fault
separates the pre-Pennsylvanian volcanics from the Pennsylvanian Rhode Island
Formation.

Just north of where the Cliff Walk leaves the sea cliff to pass behind
the brick buildings, climb down over the sea wall to examine sandstone, silt-
stone, shale, and coal of the Pennsylvanian Rhode Island Formation. A pro-
minent cleavage striking N25°E and dipping 55°W nearly obscures folded and
faulted bedding. Coal beds seem to localize the faulting. Bedding, cleavage,
and faults are all sub-parallel. In spite of the strong deformation, fossil
leaf impressions have been found at this outcrop.

Leave the Cliff Walk and return to the cars at the large N60°W striking
quartz vein with brecciated Rhode Island Formation.

Return to Bellevue Ave.

15.2   Turn left (S.) onto Bellevue Ave.

16.0   Bellevue Ave. turns right (W.).

16.2   Road turns right (N.) and becomes Coggeshall Ave.

16.3   Turn left (W.) onto Ocean Drive.

17.2   Aplite B-1 in Table 1 comes from the outcrop on N. side of road
        across from Hazard's Beach. The contact with the volcanic unit
        is just west of ths outcrop. A large inclusion of the volcanic
        unit can be seen along the west shore of Lily Pond. Outcrops
        along the road here on are in the volcanic unit.

18.1   Intersection of Brenton Rd. Outcrop in the triangle between
        the roads appear to be a basaltic andesite to andesite flow.

18.4   Cross fault contact between sediment unit and volcanic unit
        (not exposed).

18.8   Intersection of Harrison Ave. Continue W. on Ocean Drive.

18.9   STOP 3. Sediment unit in the Brenton point area and Lunch Stop.
        Park off Ocean Drive on the north side of the road. We will make a
        stop here to look at the conglomerates containing carbonate pebbles
        and to look at some east-west trending structures which may be pre-
        Pennsylvanian in age. The sedimentary aspects of this stop and
        some of the structural features are similar to those at STOP 4 and
        we will spend more time looking at them there. The sedimentological
        aspects of this stop were described by Mutch in the 1963 NEIGC Guide-
        book (Trip B, STOP 7). Mutch includes a map for the area marked
        mapped area in Figure 1. This stop will include lunch on the coast.

Walk down the ladder over the sea wall. Just southwest of the lad-
der, opposite the notation Louie and Linda 1974 in the sea wall, is
an outcrop of pre-Pennsylvanian conglomeratic rocks containing
abundant, well-rounded, carbonate pebbles. The holes in the outcrop
are places where the pebbles have weathered out. The shales sur-
rounding the conglomerate also contain carbonate. Euhedral cubes
of pyrite can be found in the green slates at this locality. A
strong penetrative cleavage and bedding are easily observed.

Walk along the beach to the southwest towards Graves Point and Brenton
Point (the area marked as the mapped area on Fig. 1 at Stop 3). The
pre-Pennsylvanian metamorphosed grey-weathering siltstone, slates,
and sandstones and the whitish-weathering siltstones exposed here
have bedding and a prominent cleavage striking east-west and dipping
to the north. The northward dip of the bedding is established by
graded bedding that can be seen in many places. A second cleavage
is visible in some places. On the surface of the prominent cleavage,
three lineations can commonly be observed: (a) a mineral elongation,
(b) a fracture lineation, and (c) the intersection of cleavage and
bedding. The first two lineations are north-south in orientation
and can be explained by the Pennsylvanian deformation. The third,
the cleavage-bedding intersection, is variable but is east-west in
some localities. The east-west features are not easily explained
in terms of the north-south trend of the known Pennsylvanian deforma-
tion and might indicate a pre-Pennsylvanian event. Offset along
numerous small faults can be observed in this section.

Go towards the steps up the sea wall approximately opposite Atlantic
Avenue. Two cleavages and a N-S lineation resulting from their
intersection can be observed in whitish siltstone at this locality.
Small folds can be seen by looking along the strike of the outcrop.
The prominent cleavage in the grey-green-weathering bed to the south
of the siltstone gently undulates along an east-west axis. A small,
deformed mafic dike, which cuts the bedding, is also present at this
locality.

We will eat lunch on this outcrop. There are restroom facilities
available at Brenton Point State Park about a third of a mile north
on Ocean Drive. We will reconvene at the north end of the parking
lot at Brenton Point State Park. In case of rain, there is shelter
at the park.

19.6   N. end of Brenton Point State Park parking lot. Proceed N. on
        Ocean Drive. Note purplish slates of the sediment unit forming
        small cliff on west side of road.

19.9   STOP 4. Sediment unit at Castle Hill.
        Park in the public parking area on Ocean Drive. Overflow cars can
        park in the lot near the summer cottages on the road to Castle Hill.
        This is private parking and should not be used without permission.

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Walk to the outcrop on the shore on Ocean Drive just south of the turn to the Castle Hill Hotel (The Castle Hill Hotel was used by Alexander Agassiz as a marine biology laboratory, one of the first oceanographic stations). Exposed at this locality is a typical section in the sediment unit. Beds of graywackes and shales, showing graded bedding, clearly indicate that up is to the north. A well developed cleavage is visible cutting the bedding. Veins filled with quartz and chlorite are common. Some kink bands are visible in the outcrop. At the south end of the outcrop is a green chlorite dike which cuts the bedding. In thin section this dike appears to be andesitic based on relict feldspar structures and ghosts of mafic phenocrysts.

Walk west along the shore past the summer cottages and round the corner heading north along the shore of Castle Hill. Observe outcrops of siltstone, shale, and sandstone as well as chlorite-albite-opaque rocks which were probably originally mafic igneous rocks. Graded bedding indicates some overturned beds near the break near Rams Head. Isoclinal folds can be seen in two localities near Rams Head. These folds are cut by cleavages which are not axial planar and are probably unrelated to the folds. The main cleavage is warped and a second cleavage is visible in some places. Most of the structural features seen here have north-south trends and are probably late Pennsylvanian in age. There is abundant evidence of small displacements along faults and joints all along the shore.

Continue walking north past the lighthouse and down into the inward indentation in the shoreline. Carbonate concretions are present in the green slate-siltstone beds at this locality. The concretions vary from 6" to 1' across and occur in a single horizon 20-25' thick. Many are weathered out and only the elongate holes are preserved. Where concretions are preserved, they are weathered brown on the surface. This is the only place in the pre-Pennsylvanian that these concretions have been found. The shales and siltstones in this area contain carbonates and are cut by carbonate veins. Cleavage and bedding are easily observed all along the shore at this locality. Walk up the hill across the Castle Hill Hotel parking lot. Follow the road back to where the cars are parked.

Continue N. on Ocean Drive.

20.0   Sharp right turn.

20.1   Turn left following the main road onto Ridge Rd.

20.7   Sharp right turn.

20.9   Stop sign. Turn left onto Harrison Rd.

21.2   Turn left at sign for Fort Adams State Park.

STOP 5. <u>Sedimentary and volcanic units in the Brenton Cove area.</u>
Park in the parking lot near the restrooms in Fort Adams State Park.
In summer there is a parking fee, but this will not apply in October.
Walk to the outcrop that parallels the road that you just drove in on.

This outcrop is composed of interbedded shales, sandstones, and con-
glomerates with interspersed quartzite boudins and is mapped as part
of the sedimentary unit. As in other places on Newport Neck, these
rocks are in the chlorite zone of regional metamorphism. Included
in the conglomeratic and sandy layers are fragments of carbonates,
shales, quartzite, chert, and volcanic fragments, and abundant sub-
hedral twinned feldspars and subrounded quartz grains. All of the
clastic rocks are very rich in iron oxides. The quartzite boudins
are composed of rounded to subrounded grains of clear quartz sand
with a small amount of micaceous intergranular material.

Small folds are visible in the outcrop at the northern end. A good
transposition cleavage can be seen which appears to be axial planar
to these folds. The cleavage is warped but generally dips gently to
the east. A second cleavage is visible in some places. Two cleav-
ages and bedding are clearly shown at the south end of the outcrop
on the road. The outcrop is cut by numerous quartz veins which have
been folded. Slickensides are common on the face of the outcrop.
Quartz boudins are visible in several places along the outcrop. One
giant boulder 15x40' can be seen by the fee collection station.

Walk back to the parking lot and walk down to the shore northeast of
the old artillery stable. The outcrops are again primarily sandstone
and shale, with boudins of quartzite. Also present at this locality
is a layer several feet thick of pink dolomite cut by veins of cal-
cite and a yellow mineral which may be serpentine. Dolomite pebbles
resembling the dolomite to be seen at the Ida Lewis Rocks at STOP 7
are reported to have been seen by Hitchcock at this locality in 1860
by Dale (1884).

Follow along the shore to the south going towards the head of Brenton
Cove. At the fence there is a small flint outcrop of sandstone and
shale containing red jasper pebbles. Pebbles of this type are also
found in the volcanic conglomerates on the east shore of Brenton Cove.

At low tide it is possible to walk around the end of the cove to the
outcrop forming the cliff on the east side. The fault separating
the volcanic and sedimentary units comes through the head of the
cove in the open area. The cliff on the east side is volcanic con-
glomerate composed of pebbles of volcanic and volcaniclastic sediment
as well as some pebbles of quartzite and shales not necessarily re-
lated to the volcanic rocks. The conglomerates vary in grain size
and are interbedded with dense, grey-green, flinty rocks which are
probably volcanic siltstones.

Go back to the parking lot and walk north along the west side of
Brenton Cove past the pier to the part where the circle drive from
Brenton Village intersects the road. At low tide, outcrops offshore
can be seen which contain pink and grey dolomite, quartzite-talc
schists, and shales. Veins of quartz are very abundant in these
rocks. Dale (1884) reports finding red jasper pebbles in these
shales.

Return to Harrison Ave.

21.8   Turn left (E.) onto Harrison Ave. Cross fault (not exposed)
        between volcanic unit and sediment unit about at intersection
        with Hammersmith Rd. Outcrops east of here are in the volcanic
        unit.

22.3   Harrison Ave. goes left. Continue straight ahead. Intersection
        with Beacon Hill Rd. Turn right (S.) for Stop 6.

        Stop 6. Accretionary lapilli in the volcanic unit.
        Park on the left (west) side of the road just south of the flat
        outcrop. No hammers in this outcrop, please. Walk back to
        the flat outcrop.

        Rocks in the volcanic unit containing accretionary lapilli are
        exposed on the low, flat, glacially smoothed outcrop at this
        locality. The lapilli are peasized and smaller structures which
        appear as darker spots on the lighter groundmass. The lapilli
        were probably originally composed of volcanic ash, but have
        been metamorphosed and are now primarily a quartz-muscovite-
        chlorite assemblage. According to Moore & Peck (1962), the
        following observations may be made on the occurrence of accre-
        tionary lapilli. Accretionary lapilli of this type are thought
        to form in ash-charged volcanic clouds by accretion of ash to
        cores of ash formed by condensation of water and then to fall
        to the ground like hailstones. The presence of accretionary
        lapilli probably indicates that the rocks in this outcrop were
        deposited on land or possibly in shallow water. The eruptive
        vent was likely within one hundred miles and much more likely
        within ten miles. Accretionary lapilli from known vents are
        usually found within several miles of the source.

        Go back to the cars and turn around, heading north back to the
        intersection.

        Turn right (E.) at intersection.

22.6   Intersection with Brenton Rd. Continue straight ahead (E.)

22.7   Intersection with Wickham Rd. Turn left (N.).

22.8   Stop sign. Harrison Ave. Continue straight ahead (N.).

23.1   Road turns right, and becomes Wellington Ave. Park here for
        Stop 7. Arch on left reads Ida Lewis Yacht Club.

STOP 7. Carbonate rocks at Ida Lewis Rocks.
Park in the public parking area on the street. The Ida Lewis Yacht
Harbor is private property and permission must be obtained from the
people at the harbor. Please limit hammering so as not to mar the
appearance of the outcrop. Walk out along the pier to the two small
islands at the end.

The western island and the western half of the eastern island are
composed of light grey to bluish dolomite. The eastern half of the
eastern island is a pinkish and yellowish dolomite that contains
some interlayered thin, purple and rarely green slates. In one
locality there is a lens of purple slate overlain by an interbedded
sequence of purple slates and dolomites. Two cleavages can be seen
in the slate.

Carbonate rocks associated with talc and serpentine occur at the
promentory a quarter of a mile southwest of here. Carbonates have
been reported in association with green shales underlying Goat
Island (Foerste, in Shaler, Woodworth and Foerste, 1899). A fault
has been mapped by most workers between the carbonate rocks and the
volcanic rocks directly south of here.

No macrofossils have been found in these outcrops of carbonate rocks.
Two large hand specimens from the eastern island at this stop were
dissolved in HCl but no silicified microfossils were found. Either
these rocks were originally nonfossiliferous or any fossils present
were completely obliterated by the Pennsylvanian metamorphism and
deformation. The lack of fossils supports the contention that these
rocks are Precambrian.

Continue E. on Wellington Ave.

23.5   Little League field. Retrieve cars. Road log continues to optional
        Stop 8 at Sachuest Point.

23.7   Thames St. Turn left (N.). Turn immediately right (E.) just N. of
        Shell station onto Lee St.

23.8   Turn left (N.) onto Spring St.

24.3   Stop light. Turn right (E.) onto Memorial Blvd.

24.5   Stop light at Bellevue Ave. Continue straight ahead (E.) on
        Memorial Blvd.

25.8   Just past the First Beach continue straight ahead (E.) on Purgatory
        Rd. Main road bears left.

26.7   Sign on right for Purgatory Chasm; stretched cobble conglomerate
        in Pennsylvanian Rhode Island Formation.

26.8   Bear right following the shoreline.

27.1   Bear right.

27.6   Bear right.

28.2   Gate to Sachuest Point. It is not clear whether permission is
        needed to continue beyond this point; when the locality was
        visited in April 1976 the gate was open and unattended.

        Stop 8. Unconformity at Sachuest Point
        The geology of this stop is described and illustrated with a
        geologic map in Mutch (1963a). The outcrops are on the east
        shore of Sachuest Point close to its southern tip. Quartz
        granule conglomerate similar to that seen at Stop 1 interbedded
        with black shales comprise the Pennsylvanian rocks above the
        unconformity. Pre-Pennsylvanian rocks are poorly sorted
        siltstones, sandstones, and conglomerates, commonly with
        volcanic detritus.

Trip F-6

ALLEGHENIAN DEFORMATION, SEDIMENTATION, AND METAMORPHISM
IN SOUTHEASTERN MASSACHUSETTS AND RHODE ISLAND

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Introduction

The Narragansett Basin of southeastern Massachusetts and Rhode Island is a topographic and structural depression that contains a thick sequence of sediments and rests unconformably upon an older basement of dominantly granitic rocks (Figure 1). These clastic sediments are well indurated, and have been progressively metamorphosed and deformed to the south.

Recently there has been renewed interest in the coal-bearing strata, and an exploration of the coal deposits in the Narragansett Basin has just begun (Skehan et al, 1976). This project entails detailed field and petrographic studies coupled with an extensive drilling program. The early results of this project suggest that the metamorphic and tectonic history of this region is considerably more complicated than previously believed. The purpose of this trip is to give a preliminary account of this work and to point out the salient field relations we believe critical to any regional synthesis of this part of New England. This trip is meant to complement the other trips in this volume that deal with the Narragansett Basin (Chapple and Kay; Lyons and Chase; Mosher and Wood), and the 1963 NEIGC (which concentrated on the geology of the Narragansett Basin).

The first stop will focus on the Dighton conglomerate, the youngest unit in the Basin, where primary structures are well preserved. The next three stops, in the Portsmouth, Rhode Island area, will examine the sedimentary and structural relationships in the vicinity of the most productive coal mines in the Basin. Then stops at Beavertail (on Conanicut Island) and Narragansett Pier, in metamorphosed and multiply deformed rocks that may be significantly older than their assigned Upper Paleozoic ages, are scheduled. The final stop, in Providence, Rhode Island, will illustrate the fact that the accepted structural interpretation of the Pennsylvanian sediments - that they have been deformed into a northward trending syncline - may be an oversimplification.

An understanding of the evolution of the Narragansett Basin is critical to any model for the evolution of New England, as the Basin represents the largest exposure of Late Paleozoic rocks in New England. The rich body of literature,

KEY

☒	NARRAGANSETT PIER GRANITE
◩	DIGHTON CONGLOMERATE
☐	RHODE ISLAND FORMATION
☰	WAMSUTTA FORMATION & PONDVILLE FORMATION
⧄	PRE-CARBONIFEROUS (?) ROCKS
⊠	PRE-CARBONIFEROUS ROCKS
---	FAULT
●	MAJOR FLORAL LOCALITIES
①	FIELD TRIP STOPS

0 2 4 6 8 10
MILES

Figure 1 - Generalized geological map of the Narragansett Basin (Modified from Quinn, 1971; Shaler, 1899).

reaching well into the nineteenth century, underscores the realization. Recent articles that ably review the geology of the Narragansett Basin include Quinn and Oliver (1962), Quinn and Moore (1968), and Mutch (1968). In addition, the bedrock geology map of Rhode Island (Quinn, 1971) covers much of the Basin. The following sections summarize the geology of the Narragansett Basin; the reader is referred to the above-mentioned works for further information.

Stratigraphic Relationships

Four, or perhaps five, formations of Pennsylvanian sediments are recognized in the Narragansett Basin. They are briefly described below, going from oldest to youngest.

1. The Pondville Formation consists of arkosic sandstones and conglomerates and forms a discontinuous basal unit along the margin of the Basin. The type locale for the formation is the Norfolk Basin, a similar Pennsylvanian Basin to the north of the Narragansett Basin.

2. The Wamsutta Formation consists of conglomerate sandstone and shale characterized by a reddish color and the presence of volcaniclastic sediments and flows. It is restricted to the northwestern part of the Basin.

3. The Rhode Island Formation was originally defined as "all the horizons on which coal has been reported" (Shaler and others, 1899). It is now believed to consist predominantly of gray sandstone (arkoses and feldspathic graywackes), siltstone, conglomerate, shale and coal. The formation comprises 80+ percent of the Basin, and of the lithologies listed above, the sandstone is the most common.

4. The Dighton Conglomerate consists of three thick conglomeratic horizons that apparently form the cores of synclines (Figure 1). Lithologically, it is identical to the conglomeratic horizons within the Rhode Island Formation.

5. The Purgatory Conglomerate is confined to the southern (Newport) part of the Basin, and consists of a stretched pebble (to boulder) conglomerate. It is probably correlative with the lower part of the Rhode Island Formation (Mutch, 1968), and not the Dighton Conglomerate.

Scarcity of outcrop, rapid facies changes, and structural complexities restrict the measurements on the thickness of this stratigraphic sequence to rough estimates. The thickness probably lies between 2,000 and 12,000 feet, with the true value probably near the upper limit (Mutch, 1968). On the basis of an investigation of the sedimentary structures and petrology of the Narragansett Basin, Mutch (1968) concluded that the region was an isolated inter-montane basin, possibly fault bounded in some regions, and characterized by the rapid deposition of various types of fluvatile sediments.

The occurrence of well preserved floral assemblages in many parts of the Basin (see Figure 1 for locations) has allowed for the first time the widespread accurate dating of the sediments. The rocks range from Westphalian B to Westphalian D, and may be as young as early Stephanian (Lyons and Darrah, in press, 1976; Lyons and Chase, this volume). These ages are consistent with radiometric dates obtained on metamorphosed sediments in the southern part of the Basin, and with granites probably intrusive into these metasediments (Quinn and Moore, 1968).

Structure

As a first approximation, the Rhode Island portion of the Narragansett Basin forms a northeast-trending synclinal trough (Quinn and Oliver, 1962). On closer examination, however, the structure of this part of the Basin is considerably more complex, with easterly trending folds and thrusts having at least local importance (Stop 7). In Rhode Island and southernmost Massachusetts, structural patterns are conspicuously defined by stretched pebble conglomerates and bedding/cleavage relations (Stops 1 and 7 of this trip; Mosher and Wood, this volume). These very features have attracted the attention of geologists since the early nineteenth century. In the southernmost part of the Basin at Beavertail, at least two distinct episodes of folding, separated by periods of brittle deformation and vein formation, are evident (Stop 5).

The Massachusetts part of the Basin, which is less intensely deformed, contains three east-northeast trending synclines (Figure 1). The slightly deformed Dighton conglomerate, seen at Stop 1, lies within the southernmost syncline. Paucity of outcrop prevents recognition of the anticlines that presumably separate these depressions, as well as any structural relationships within the northeastern part of the Narragansett Basin.

The western margin of the Basin is known to be fault bounded (Quinn, 1971), while some sections of the eastern margin represent an unconformity between the Pondville Formation and the underlying granite gneisses (Mutch, 1968). North-south striking faults are common throughout the Basin, although east trending faults are also present (Stops 2, 7). It appears that the Rhode Island part of the Basin consists of a number of blocks elongate in a north-south direction. Whether these blocks are separated by predominantly normal or thrust faults is not clear, as both types are recognized in local field exposures.

Several smaller Carboniferous basins also occur in southeastern New England (Worcester Basin, North Scituate Basin, Norfolk Basin, Woonsocket Basin, and possibly Boston Basin), and elsewhere (Quinn and Oliver, Jr., 1962; Mutch, 1968. Quinn has argued that the presence of older rocks near the mouth of Narragansett Bay suggests that this location is the southern terminus of the Pennsylvanian Basin, and if the rocks mapped as Rhode Island Formation at Beavertail (Stop 5) and South Kingston (Stop 6) are interpreted as representing older metasediments, Quinn's conclusion is strengthened.

Metamorphism

Nearly all of the Massachusetts part of the Basin lies in the subchlorite zones. In Rhode Island, the sediments are progressively metamorphosed to the southwest, and this terrain has been classified as intermediate between Miyashiro's (1973) Barrovian and Buchan metamorphic facies series by Grew and Day, 1972. Grew (1974) has also carried out a detailed study of carbonaceous material from sediments of the Narragansett Basin that have undergone varying degrees of metamorphism. His results show that a variety of systematic changes occur in this material, and that they may prove to be useful indicators of metamorphic grade.

The upper limit of metamorphism is uncertain as sillimanitic and/or migmatitic schists mapped as Rhode Island Formation may actually repreent pre-Pennsylvanian metasediments (Stop 6). In any case the metamorphism is at least staurolite grade. A related problem is the extent (if any)) to which the Pennsylvanian sediments are contact metamorphosed by the Narragansett Pier granite. In a migmatite taken as a typical example of the contact between these two rock types (Stop 6), the granite may not be the Narragansett Pier and the host rock is most similar to outcrops of Precambrian Blackstone Formation

that are exposed in the vicinity. Finally, a recent study of the petrography
of the Pennsylvanian metasediments in the southernmost part of the Basin (Milne,
1972) suggests that at least some of the rock reflects a polymetamorphic history.
This observation, if true, can be most easily accounted for by having these rocks
represent older metasediments that were metamorphosed again with the Pennsylvanian
sediments.

Itinerary

The trip begins and ends at Stop 7, the parking lot of the University
Heights Star Market on North Main Street, Providence, Rhode Island. To reach
the market from Boston proceed south on I-95 towards Providence. Take Exit 24
(Branch Avenue Exit). Turn left on Branch Avenue and proceed 0.4 miles to North
Main Street. At North Main turn right and continue for 0.2 miles to Doyle
Avenue. Turn left on Doyle and make the first right turn into the Star Market
parking lot. Depending on the size of the group, some stops may be eliminated.
Departure time is 8:00 a.m., sharp, and participants are urged to arrive in
time to consolidate the number of vehicles.

Mileage

0.0   From Star Market parking lot, take Doyle Avenue Exit, turn left on
        Doyle, then make an immediate right on North Main Street.

0.2   Bear left off of North Main Street onto Branch Avenue (fire station
        on left).

0.6   Turn left off of Branch onto I-95 south. Watch for I-195 signs
        using two left lanes.

2.8   Bear left onto I-195 from I-95.

12.4   Large roadcut of Dighton conglomerate with sandstone lenses, that
        is similar to the first stop. Bedding trends N.70°E. 10°S, and a well-
        developed fracture cleavage (N.70°W. 80°S.) is present.

14.9   Exit 19 (Swansea-Somerset). Leave I-195 and turn left (WNW) on
         Route 6 (Fall River Avenue). The outcrops along the exit ramp are
        the first stop. Caution: Do not take the first Route 6 exit travel-
        ing east from Providence.

15.5   At the traffic light turn left onto Maple Street.

15.9   From Maple Street turn left at Old Warren Road (marked by dangerous
        intersection sign) and drive to the end of the street. Park, and
        walk approximately 50 yards to outcrops on access ramps to I-195.

16.2   Stop 1. Dighton Conglomerate - Outcrops along access ramps.

        This outcrop of Dighton conglomerate is typical of the formation,
        and is located on the northwestern limb of the Dighton Syncline
        (Figure 1). Here, it consists primarily of rounded quartzite
        cobbles with subordinate amounts of rounded granite cobbles and slate
        pebbles. There is very little matrix, and clasts commonly are
        mutually indented. Lenses of faintly cross-bedded sandstone form
        approximately ten percent of the exposure; one of them contains a few
        plant fragments. These features imply a fluvatile environment, and

it has been suggested that these sediments were deposited by braided
streams (J. Collinson, 1976, pers. comm.). Unfortunately, the three
dimensional configuration of the conglomerate and sandstone bodies
is not exposed; without this information one cannot prove the existence
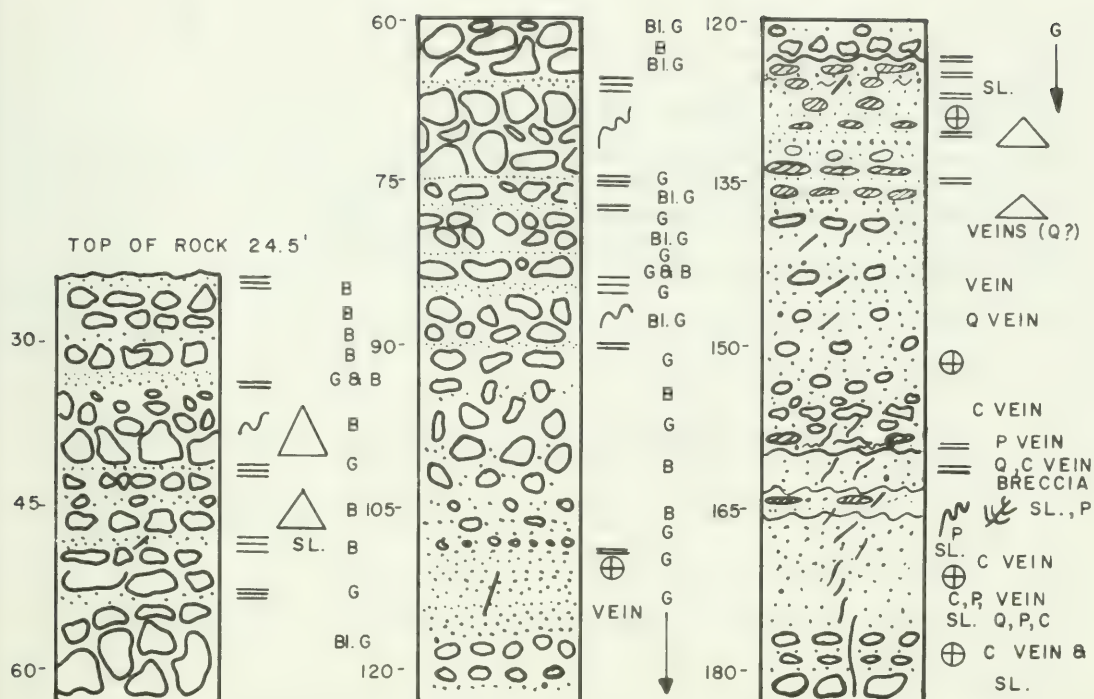of braided streams.

These thick conglomerate beds of the Dighton Formation are indistin-
guishable from thinner conglomeratic lenses within the Rhode Island
Formation. Some insight into the relation between these two forma-
tions may be gained from consideration of a drill core that was re-
cently obtained from the middle of the Dighton Syncline (Figure 2).
The core begins in typical Dighton conglomerate with brown matrix and
grades downward into fresher, gray conglomerate. Gradually down the
core, sandstone and siltstone layers become more abundant, and eventu-
ally dominate. Bedding is almost horizontal. A fault near the bottom
of the core is suggested by the abundance of calcite veins and slicken-
sides. The preferred interpretation is that the Dighton conglomerate
grades conformably downward into the Rhode Island Formation, and that
there are no major breaks in the record. We consider the brown stain-
ing of the upper part of the core to represent weathering, and not to
be a feature characteristic of the Dighton (as suggested by Shaler,
(1899). The contact between the two formations is placed at the point
where a dominant lithology of conglomerate gives way to a dominant
lithology of sandstone and siltstone.

This outcrop of Dighton is also slightly metamorphosed, and chlorite,
epidote, quartz, and calcite occur in the matrix and along joints.
The structural relations observed at this outcrop are listed in
Table 1, and the salient points summarized below.

1. Analysis of cross-bedding in the sandstone lenses indicates
    that the Dighton is not overturned; it also has a fairly
    uniform strike and dip at this outcrop.

2. The cobbles are slightly elongate, with the maximum direction
    of elongation (N.20°E.) at an oblique angle to the general ENE
    trend of the Dighton syncline: The cobbles are also offset
    along shear fractures.

3. A prominent joint set controls the shape of the outcrop.

Table 1 - Structural Relationships at Stop 1

Type of Measurement	Attitude
1. Contact between conglomerate and sandstone layers	N.80°E. 30-40SE.
2. Cleavage	N.80°E. 60SE.
3. Longest axis of pebbles	N.20°E 50
4. Joint; not mineralized	N.80°W 45-60NE.
5. Joint; mineralized, parallel to plane of flattening of pebbles, most prominent	N.30°E.55SE.
6. Mullions on mineralized joints	N.85°E. 35
7. Quartz veins	N.90°E. 65N.

TOP OF ROCK 24.5'

60-   Bl. G
        B
        Bl. G

75-   G
        Bl. G
        G
        Bl. G
        G
30-   G & B
        B
        B
        B
90-   G & B
        Bl. G

        B
        G
105-   B

        B
        G
        G
        G
        VEIN
        G
120-

120-   G
135-

150-

165-

180-

VEINS (Q?)

VEIN

Q VEIN

C VEIN
P VEIN
Q, C VEIN
BRECCIA
SL., P

SL. C VEIN
C, P, VEIN
SL. Q, P, C

C VEIN &
SL.

LEGEND

~~ MUDROCK

...... SANDSTONE
        (FINE TO COARSE)

.:o:o PEBBLY SANDSTONE

oo CONGLOMERATE
     (FINE PEBBLE TO
      SMALL COBBLE)

B   BROWN   UNIFORM COLOR

G   GREY

Bl. G BLUE-GREY

P   PYRITE

Q   QUARTZ

C   CALCITE

SL. SLICKENSIDES

≡   LAMINATIONS

~   CONVOLUTED BEDDING

△   GRADED BEDDING

⊕   HORIZONTAL BEDDING

⊘⊘ RIP-UP CLASTS

     FOSSILIFEROUS

/   VEIN, FRACTURE

Figure 2 - Diagrammatic representation of a drill core from
            Rehoboth, Massachusetts. The core passes
            downward from Dighton Conglomerate into Rhode
            Island Formation. (Paul Lyons and Linda Oliver, Analysts)

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17.1   Return to I-195, and enter I-195 going east to Fall River.

20.3   Samll outcrop of Dighton conglomerate.

23.4   Exit off I-195 onto Route 24 south..

26.4   Bulgarmash Granite cropping out in Route 24 median.

26.7   Bulgarmash Granite cropping out under Route 24 overpass.

27.0   Roadcut Bulgarmash Granite, fractured and jointed.

28.4   Roadcut Bulgarmash Granite

        Caution: Continue straight through on Route 24. Do not take Mt.
        Hope Bridge Exit. Look for Turnpike Avenue Exit.

32.2   Large roadcut of Rhode Island Formation under Sprague Street Bridge.

32.5   From Route 24 get off at the Turnpike Avenue Exit.

32.8   From exit ramp turn left onto Turnpike Avenue and go to the first
        stop light.

33.1   At stop light turn left onto West Main Road (Route 114).

33.3   Make the first right-hand turn onto Willow Lane and drive straight
        ahead.

33.8   Kaiser Aluminum plant on left-hand side.

33.9   At the pavement's end continue on the dirt road 0.2 miles to the
        gate on the left side of the road.

34.1   Stop 2. Mine dump at the site of the Portsmouth Coal Mine.

        Good specimens of meta-anthracite may be collected here, the site of
        the largest of several coal mines on Northern Aquidneck Island.

        These mines were worked intermittently during the eighteenth
        through early twentieth century, and approximately one million tons
        of coal were removed from here between 1860 and 1913. Mining was
        mainly confined to the middle of three coal seams, and this seam
        was worked from two slopes, 1800 feet apart, that extended down dip.
        Figure 3 shows the reported limits of mining at this site and the
        location of other mines in the area. The seams averaged 30-36 inches.
        However, lenses up to 12 feet thick were common, and in general, the
        seams thickened and thinned. The coal itself is a typical well cleated
        meta-anthracite with a brilliant luster and occasional resinous
        (exinite) layers within a predominantly vitrinite matrix. Recent
        analyses of dump samples from the Portsmouth Mine by the United States
        Bureau of Mines indicate the coal varies in volatile matter from
        4.4 percent to 7.2 percent (d.a.f.), in B.T.U.'s from 12 to 13,000
        and in sulfur content from 0.1 percent to 0.4 percent. A more
        complete description of the history of mining at Portsmouth, Rhode
        Island, is given in Toenges et al (1948), and the geology of the
        region is summarized below.

        The lithologies are black slate, medium-to-fine-grained sandstone,

Figure 3 - Generalized Geologic map of northern
Aquidneck Island, Rhode Island.
Structural data, in part, from
Toenges, et al (1948).

AQUIDNECK ISLAND

STOP 2
PORTSMOUTH MINE
(SLOPE)

KAISER
PLANT

WILLOW LA.

CASE MINE

BUTTS HILL

TRACE OF
MINED AREA

IRI

STOP 3
30

SHORE LINE
EXPOSURE

COREY'S LA.

STOP 4 QUARRY

KEY

STRIKE AND DIP OF BEDS
OVERTURNED
FAULT, LOCATION INFERRED
MINE OR PROSPECTIVE MINE
QUARRY
ROAD, STATE HIGHWAY
IRI   U.S.B.M. CORE HOLES
AREAL EXTENT OF PORTSMOUTH

N

0   2000'
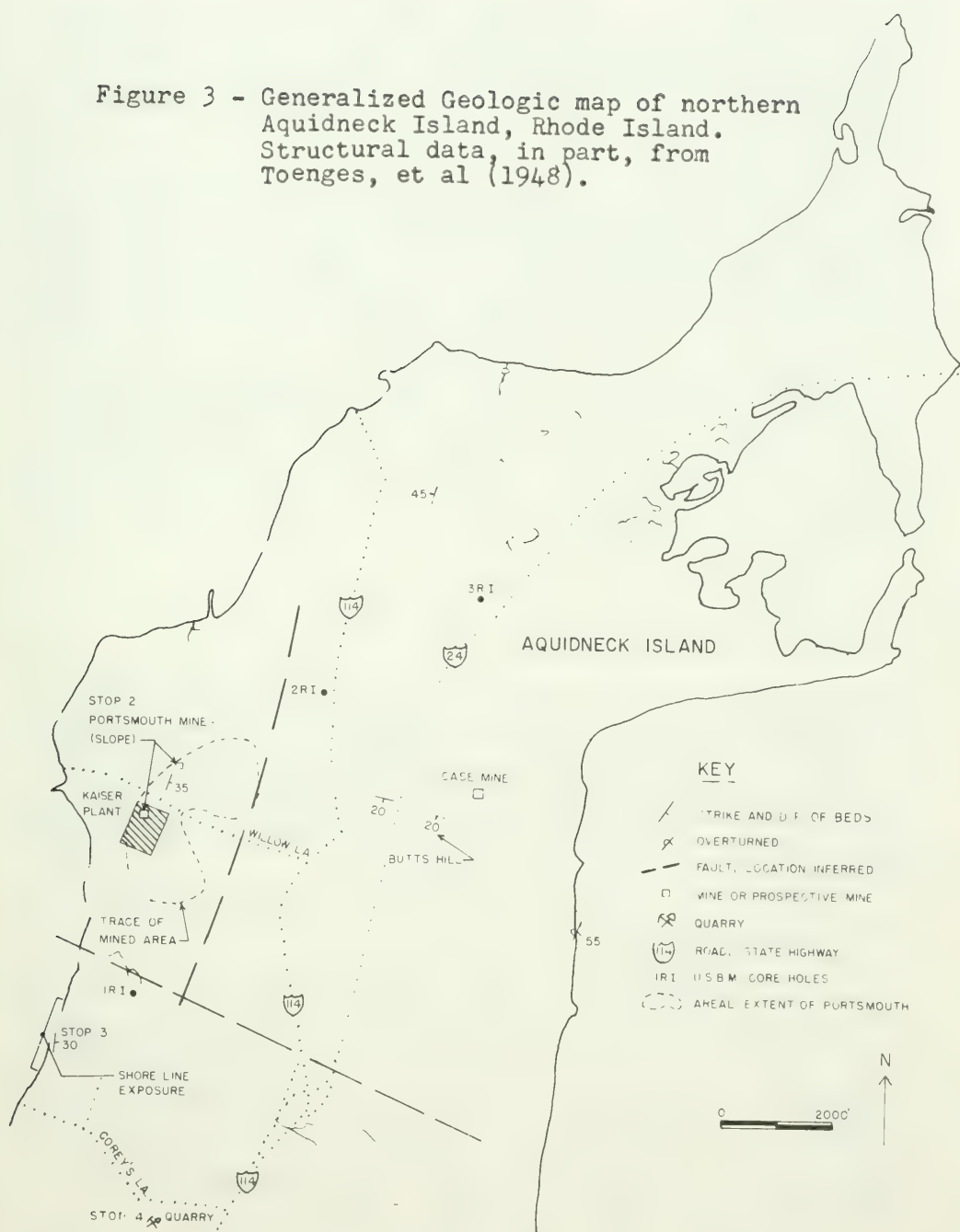
and meta-anthracite. The stratigraphic relations and paleo-environment of this part of the Basin are discussed under Stop 3, which represents a well-developed stratigraphic section. Slates from this stop have been classified as chlorite grade (Quinn, 1971), and this conclusion is consistent with the structural state of carbonaceous material in the coal and associated carbonaceous slates (Grew, 1974).

The dominant structure of Aquidneck Island has been considered to be a north trending syncline, with the Portsmouth Mine on the west limb. Assuming no other structural complications, the U.S.B.M., in 1948, drilled boreholes along the strike (Figure 3; I.R.I. and 2 R.I.) of the coal seams worked at the Portsmouth Coal Mine. In both of these holes and in an additional one to the northeast (Figure 3; 3 R.I.), no mineable coal seams were encountered, and it was concluded that the seams were ones of limited extent that had been essentially mined out. Recently, an alternate interpretation of the structural relations has been put forth by William Barton (pers. comm., 1976), which holds that north-trending and east-trending faults (Figure 3) separate the Portsmouth Mine from the three boreholes. According to this interpretation, the seams are faulted out, and consequently one of the goals of the Narragan-sett Basin Exploration Project is to test this model through additional drilling in the Portsmouth area.

34.9   Return to Route 114, and turn right.

36.1   Roadcut of Rhode Island Formation (N60°E 10-15 SE).

36.2   From Route 114 turn right at Cory's Lane, following signs for Ports-mouth Abbey School. Drive 0.6 miles on Cory's Lane, bear right after the Portsmouth Abbey Hockey Rink, and continue into the school's parking lot on the left. We will eat lunch here, after the next stop. Stop 3 is located along the shoreline, extending from the Portsmouth Abbey School's Boathouse northward. Obtain permission and detailed directions on how to get to the Boathouse at the Administration Building off the parking lot.

36.9   Stop 3. Shoreline exposures of Rhode Island Formation, northwest Aquidneck Island.

North of the Abbey Boathouse, a nearly continuous section of fossiliferous slates and meta-sandstones crop out for approximately 2000 feet. Since the shoreline, at this location, is subparallel to the trend of bedding, which strikes N30°E and dips easterly at 30°, only about 200 feet of stratigraphy is traversed. The rocks themselves have been metamorphosed to chlorite grade, and exhibit two well-defined cleavages and at least two generations of quartz veins. In addition, well-developed floral assemblages from the middle of the section indicate the sediments are Westphalian D or Stephanian A in age (P. Lyons, 1976 pers. comm.). Good specimens are available for collection here.

Figure 4 illustrates schematically the pre-metamorphic stratigraphy for this section of the Rhode Island Formation, with the Boathouse at the top of the section, and the northernmost outcrop at the bottom; the section is best seen walking from the northernmost outcrop of metamorphosed mudstone south towards the Boathouse (i.e., up section).

The section consists of two coarsening up sequences, in which the sedi-ments grade upward by alternation between mudstone and medium-grained

sandstone (Figure 4). The types of sediments and their internal struc-
tures present at this locality suggest a dominantly floodplain deposi-
tional environment interrupted by occasional pulses of spreading sand
lobes. Two likely explanations are offered for the cyclic nature of
this section: First, the crevassing of a levee during floods resulted
in the build-up of a lobe of relatively coarse material on the flood-
plain; with the closure of the break in the levee mud would again be
deposited on the floodplain. This crevassing of the levee has oc-
curred twice, resulting in two coarsening up sequences. The other ex-
planation holds that variation in the grain size of the sediments re-
flects lateral migration of a levee. Additional information describing
the three dimensional geometry of the lithologies is necessary, however,
before either explanation can be favored.

Had more stable conditions existed, it is likely swamps would have
evolved on the floodplain, giving rise to a coal producing environment
comparable to the one responsible for the coal deposits at the
Portsmouth Mine.

Leave parking lot of Portsmouth Abbey School, and turn left onto Cory's
Lane.

37.2   Turn right onto dirt trail that leads into an abandoned quarry.

37.2   Stop 4.   Quarry in Rhode Island Formation, Aquidneck Island, Rhode
                   Island.

The metamorphic and structural relationships seen here are similar to
those observed at the last stop. The rocks are phyllites and meta-
sandstone that trend N.10°E. 33°E. They were originally laminated
siltstones and fine - to medium - grained sandstone. Cross bedding
and graded bedding indicate that the rocks are not overturned. The
most interesting features are on the western (i.e., to the right -
facing the quarry) wall of the quarry. Exhibited here are syn-depositional
slump rotated blocks, several meters wide, consisting of siltstone
and fine-grained sandstone within a matrix of poorly bedded fine-
grained sandstone. These slump structures are believed to represent
features similar to the ones present in the Carboniferous Clarion
Formation of Western Pennsylvania (Williams et al 1964).

Return to Route 114, turn right, and continue south, following signs
for Newport Bridge and Naval War College.

43.3   Turn right from Route 114 at signs for Naval War College and Newport
        Bridge.

44.2   Continue following signs for Newport and Route 138.

45.0   Careful. At rotary make a 3/4 circle, exit third right, then im-
        mediately go right again. Continue on Route 138 and cross Newport
        Bridge following Route 138 around a left-hand corner, then take first
        left (North Main Road).

50.2   From Route 138 turn left on North Main Road and continue.

52.4   At warning light proceed ahead on Southwest Avenue.

53.0   After crossing beach continue following Beavertail Road.

CENTI-
METER

COMMENT

KEY

SHALE

SILTY MUDSTONE

SANDSTONE (SS)

CROSS-BEDS

CONCRETIONS
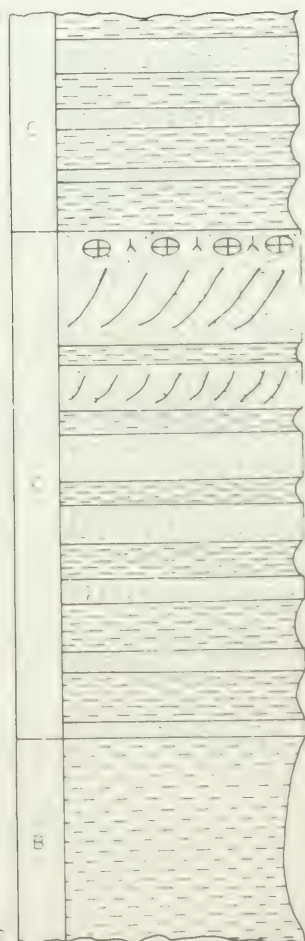
STIGMARIAN
ROOTLETS

FINE SS

SILTY SS

SILTY SS

FINE-MEDIUM SS
PLANT DEBRIS
FEW SHALE PARTINGS

FINE-MEDIUM SS

FINE SS

FINE SS

SILTY SS

SILTY SS

SILTY SS

55.4   Go left and park at Beavertail Park.

55.6   <u>Stop 5.</u>   Beavertail, Conanicut Island. (Note: Alternate parking
                  site at Beavertail Lighthouse.)

The phyllite at Beavertail (Figure 5) has long been considered of
Carboniferous age by reason of: 1) its presumed stratigraphic
continuity with Pennsylvanian dated metasediments near the Jamestown
Bridge, and 2) its apparent structural compatibility with the general
synclinal nature of the Narragansett Basin (Nicholls, 1956; Chapple,
1963). We feel that these shoreline exposures contrast sharply with
other Carboniferous rocks in the region, and that a careful analysis
of the geology of Conanicut Island in general and Beavertail in parti-
cular is crucial for an understanding of the evolution of the Narragansett
Basin. The following sections describe preliminary and tentative inter-
pretations of the field relations at Beavertail. A workshop approach
to this stop is proposed as much as a mechanism for us to share in the
insights of participants as to present the results of early stages of
our study of the Basin.

<div align="center">Structure</div>

        The structural features at Beavertail suggest that the rocks may
have a history of repeated deformation that is more complex than
other parts of the Narragansett Basin and may therefore antedate
the fossiliferous schist (of Pennsylvanian age) of Northern Conanicut
Island near Jamestown. A preliminary chronology of structural events
for this area is presented below; the numbers in parentheses refer to
field stations (see Figure 5).

    1. Deposition of beds occurred in the stratigraphic sequence
    as shown in Figure 5 (unit a is the youngest). Tops and bottom
    indicators imply that at least along the eastern shore of
    Beavertail, the stratigraphic section is for the most part
    overturned.

    2. The first tectonic event is isoclinal folding characterized
    by a bedding plane cleavage (Station 9) and accompanied by
    greenschist facies metamorphism. An axial plane cleavage,
    that is deformed by later tectonic events, is also thought to
    have formed during this period of folding.

    3. A third tectonic event is chiefly recognized by similar
    folds and localized decollement-style faults. The folding is
    developed about approximately the same axis (N-S horizontal) as
    the earlier folds, but has a different axial plane orientation
    (Stations 1, 14, 15). The sub-horizontal axial plane cleavage
    is pervasive and is the dominant one seen along the seacoast
    exposures here. In particular, note how the earlier cleavage
    and mineralized joints and faults are folded about this axis
    (Stations 3,9, 10, 13). This period of deformation is
    probably the same as the one recorded in the Carboniferous
    rocks in the northern part of the Basin.

    5. An additional period of deformation is responsible for a
    broad warping and local folding (?) of the second cleavage.
    This last episode of folding was about a new axis.
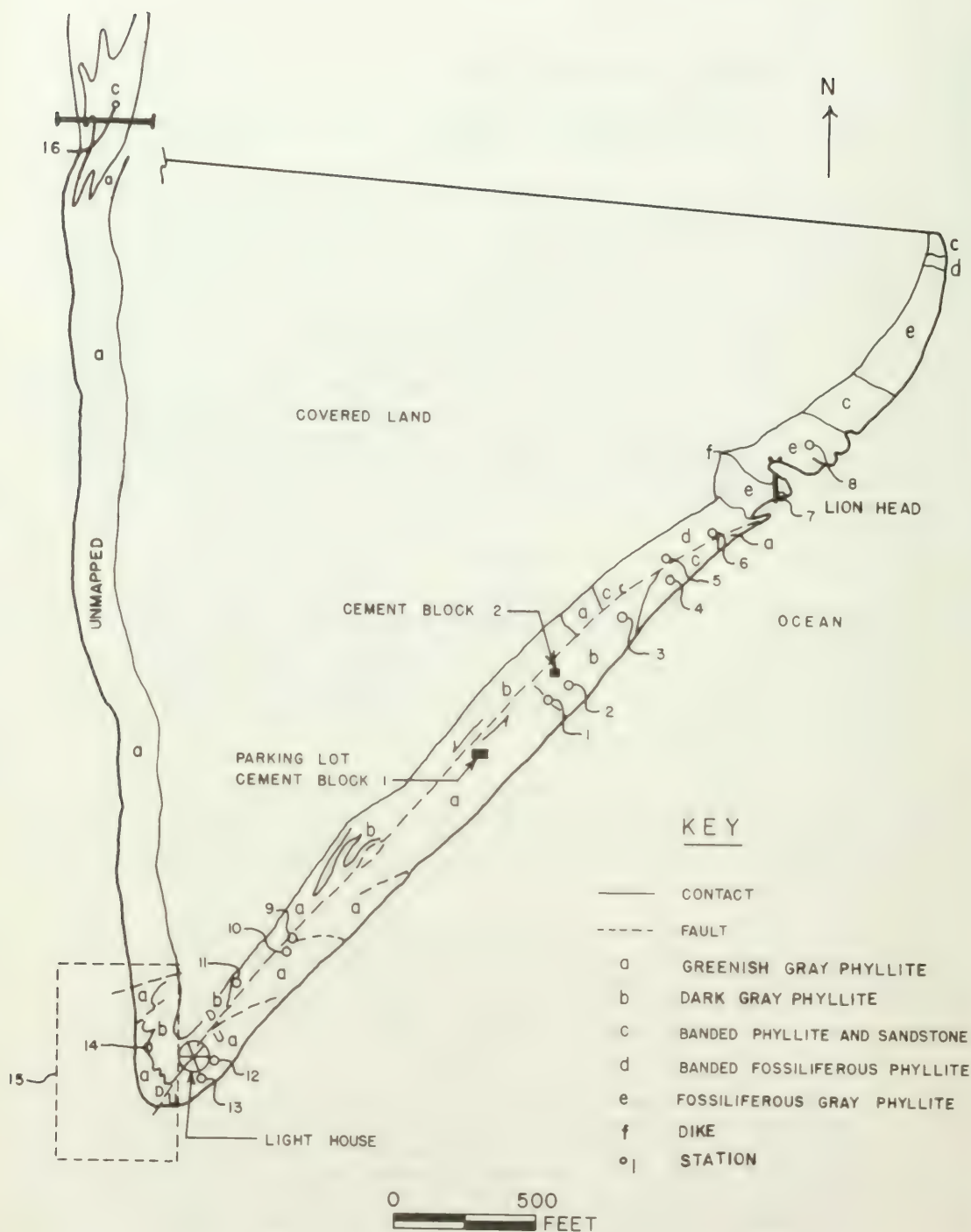
Figure 5 - Sketch map of the geology along the shore at Beavertail, Rhode Island. The stations are described in the text and figure 6.

6. Kink bands are widespread and well developed on cleavage surfaces of the second generation of folds; they are truncated by the faults described in the next stage.

7. Northeasterly striking normal faults are mineralized (Quartz + calcite) and offset older structures (Stations 5 and 11). This episode of faulting has displaced and tilted the blocks along the shore, and is illustrated by the discontinuity and angular discordance of the second cleavage from block to block. The major fault, and its consistently more easterly-striking splay faults, are referred to as the Beavertail Fault system; it has been previously described by Nichols (1956) and Chapple (1963).

Stratigraphy

The phyllites at Beavertail have been divided into five field units, based upon differences in color, layer geometry, and type of sedimentary structure. All are characterized by horizontally laminated and horizontally bedded muds with variable, though generally subordinate amounts of fine sand. Graded bedding and ripple cross bedding are found to varying degrees in all field units. The diagnostic features of these lithologies, together with those of a sixth unit that may be a "dike", are described below. Gradational to sharp sedimentary contacts exist between all five units, implying that there are at least two different gray phyllites. Our most recent mapping at other locations to the north of Beavertail has revealed the same lithologies; whether they are a repetition of the five field units so far identified is uncertain. From oldest to youngest, the field units are as follows:

a. Greenish gray phyllite. This unit is characterized by grains pyrite porphyroblasts and occasionally boudinaged by fine-grained sandstone layers.

b. Dark gray phyllite. This distinctive unit is characterized by the following features: (1) especially well developed laminar bedding; and (2) abundant concretions (Figure 6), pyrite-rich layers parallel to bedding.

c. Banded phyllite and sandstone. These two lithologies are present in approximately equal amounts. The buff colored sandstone layers contain cross bedding and graded bedding, while the phyllite layers are similar to ones found in the greenish gray phyllite.

d. Fossiliferous banded phyllite. This consists of alternation layers of very fine grained sandstone to phyllite alternating with dark gray phyllite. Of special significance is the presence of (1) unusual sedimentary structures that may be worm burrows or reqorked volcaniclastic sediments (Figure 6 d); and (2) patches of black objects that may represent deformed fossil fragments. The dark layers show graded bedding.

e. Greenish gray phyllite. This unit differs from the first in that (1) it contains less pyrite; (2) a ubiquitous mineral (anatase or altered detrital glauconite (?)) that defines a lineation; and (3) it contains shredded fragments of sandstone laminae; and (4) it has particles of material, similar to ones described for the last unit, that are comprised of possible trilobite fragments.

f. A unit previously mapped as a minette dike (Nichols, 1956)
is confined to the last stratigraphic unit. Its assemblage is
zoisite + quartz + biotite + quartz + plagioclase + calcite +
accessories. It may actually be a dike, or else a stratigraphic
horizon within the sedimentary record. In any case, it has been
deformed and records at least the last five structural events.

The sedimentary sequence of Beavertail, in spite of the complexity
of its deformation, has its sedimentary structures preserved to a high
degree. The amount of megascopically recognizable recrystallation is
small, and the two minerals now visible in hand specimens of phyllite
are pyrite (previously mistakenly identified as garnet) and a phase
that may be anatase or glauconite. In thin sections the matrix of the
phyllites is seen to consist of quartz, calcite, and micas. A deep
water, quiescent depositional environment is favored for these rocks,
based upon the following observations. First, all field units are fine
grained. Second, the scale of laminations, cross bedding, and graded
bedding is on the order of a few centimeters or less. Such an
environment could exist either at the bottom of a deep lake or in a
deep water marine environment. If possible fossiliferous material
does in fact represent trilobite fragments and/or if detrital
glauconite is identified, then a marine origin would be implied.

Reconnaissance studies by the authors on Conanicut Island sug-
gest that the meta-sediments of Beavertail may be older than the fos-
siliferous rocks near the Jamestown Bridge and younger than the por-
phyritic granite at Fort Wetherwill. These sediments may be correlative
with part of the sequence described by Chapple and Kay (this volume) in
Newport on Aquidneck Island (just northeast of Beavertail). We hope
that the fossil fragments from the phyllites will have yielded dates
that can be reported on at this conference. Meanwhile, we regard the
sediments as of Lower to Middle Paleozoic age, since they record epi-
sodes of deformation that antedate those found in the Carboniferous
rocks.

Stop 5. Field Stations

The locations of the stations described below are shown on
Figure 5.

1. Contact between greenish gray and dark gray phyllite.
Figure 6a illustrates this contact, which outlines a first
generation isoclinal fold that has been refolded about the
same axis S.25°E. 5°S. but a different axial plane (N.40°W.
5°W.).

2. Lensoid bodies that are most abundant within the dark gray
phyllite (Figure 6b). They consist of chirt margins with
phyllite matrix (calcite-rich). The ubiquitous mineral and
color layering in the host phyllite passes undeflected through
the center of the bodies, and their long axes parallel the axis
of the second generation of folds. They are believed to repre-
sent concretions, and possible are analogous to ones described
recently from the Lower Carboniferous of Great Britain (Dickson
and Barber, 1976).

3. Folded fault within the dark gray phyllite (Figure 6c).

4. Cross-bedding and graded bedding within the banded phyllite and sandstone. These deformed sedimentary structures are especially abundant in this cut.

5. Series of splay faults associated with the major northeast striking normal fault (N.75°E. 65°NW.). Slickensides are oriented N.65°W 60° . Near Lion Head several repetitions of the sequence of field lithologies are produced by this fault system.

6. Sedimentary structures in the fossiliferous banded phyllite. This lithology consists of alternating layers of light and dark phyllite. The dark phyllite has a sharp lower margin and fines upward (very fine sand to mud) over a few centimeters. The upper contact of the dark phyllite with gray phyllite is highly irregular, and suggests bioturbation (Figure 6d).

7. Possible fossiliferous debris within the greenish gray phyllite (unit e) near Lion Head.

8. Minette dike (Nichols, 1956) at Lion Head. This probable dike has been metamorphosed, folded and brecciated. There are no obvious chill zones along the dike margin or contact metamorphism of the surrounding phyllite.

9. A folded cleavage is well displayed here, with the fold axis bearing N.70°W., plunging 60° to the NW., and the axial plane striking N.80°W dipping 75° to the N.

10. The two dominant cleavages (N10°W., 30°W.; and N.10°E., 20°W.) are present at this locality.

11. The main branch of the normal fault, strik ing N.60°E. dipping 75°NW. is well developed and clearly shown at this exposure.

12. The second generation of folds are cut by a thrust fault, and both folds and fault may be folded.

13. Relationships between bedding and axial plane cleavage are particularly well displayed in cross-sectional exposures just south of the lighthouse. A good place to show students these features!

14. Refolded fold, as outlined by the contact between units a and b. The schematic cross-section in Figure 6e illustrates this feature.

15. The faulted and refolded contact between units a and b, from the lighthouse extending northwestward along the shore (Figure 6c).

16. Refolded fold, as outlined by the contact between units a and c. Isolated sections of the coastline have been mapped on both sides of Beaverneck. This station represents one of these sections. Figure 6f shows schematically this structure in cross-section.

Figure 6 - Sketches of Field relations at Beavertail (stop 5),
         Rhode Island.
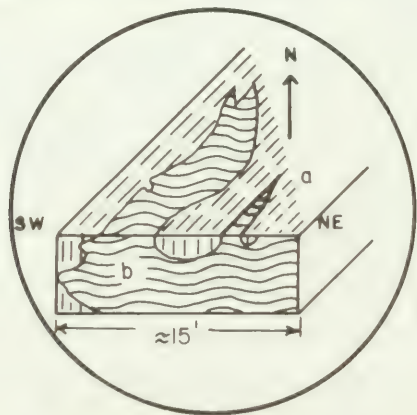
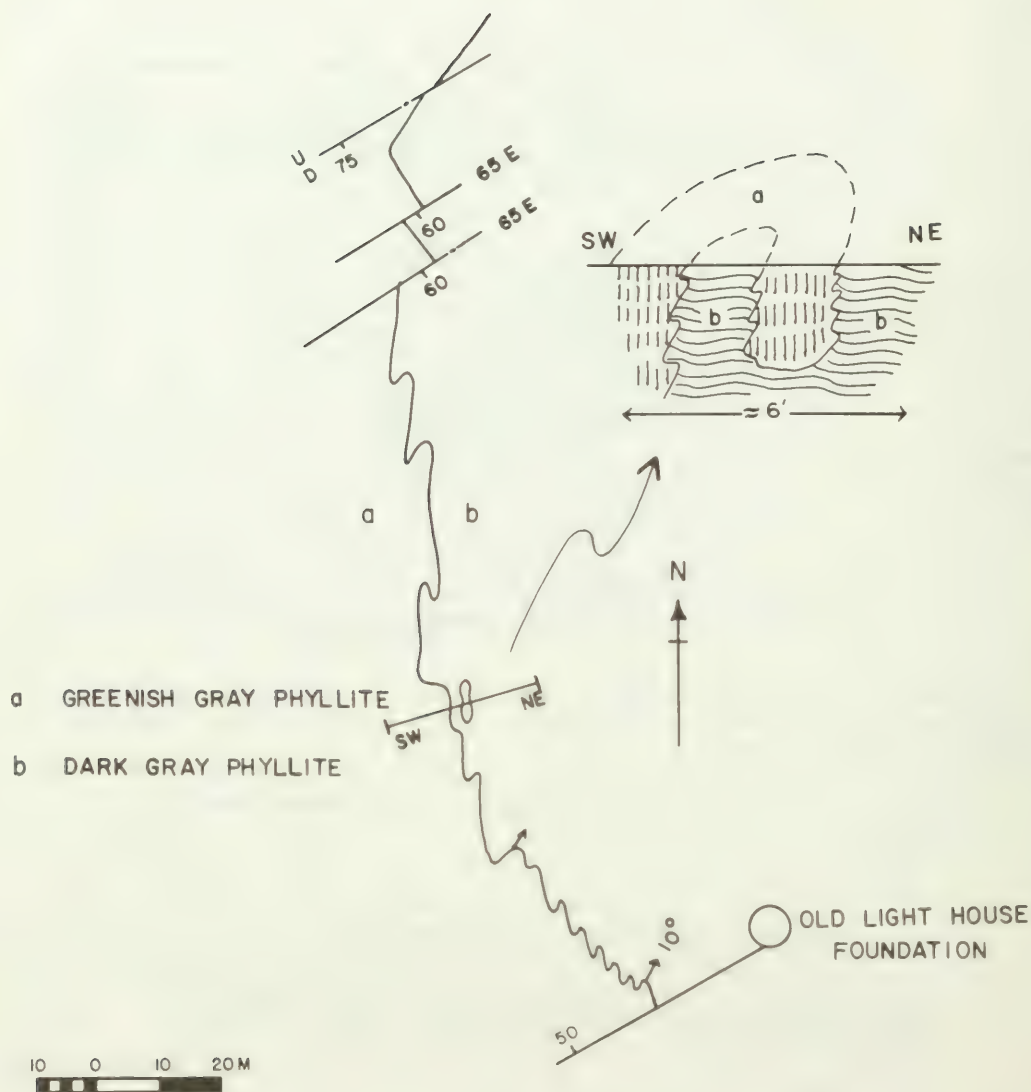6 a - Refolded contact between units a and b (station 1).
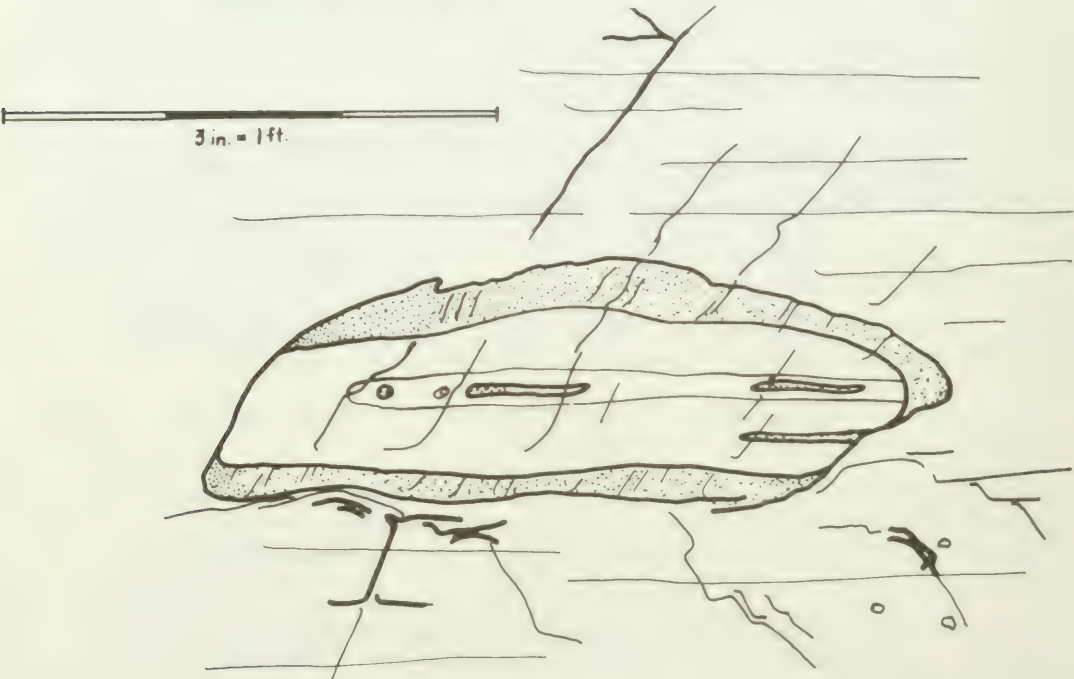
6 b - Concretions in unit b (station). The stippled areas are chert-
      rich, and the center and host rock are calcerous phyllite. The
   horizontal lines represent mineral layering.
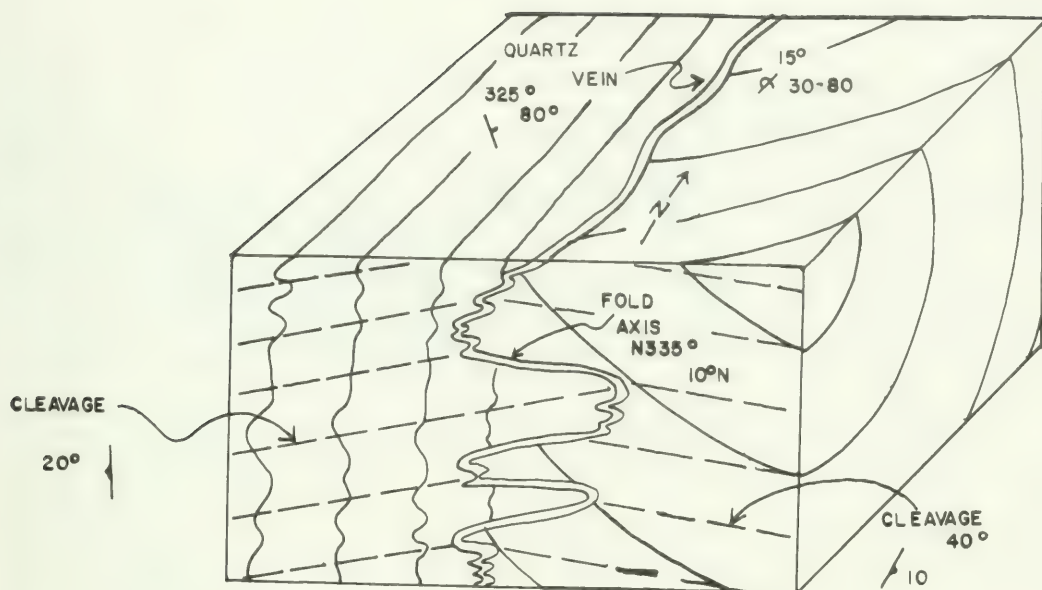
6 c - Folded Fault (station 3). The fault is now seen as a folded quartz vein that truncates structures. The edges of the diagram are approximately 5 feet.
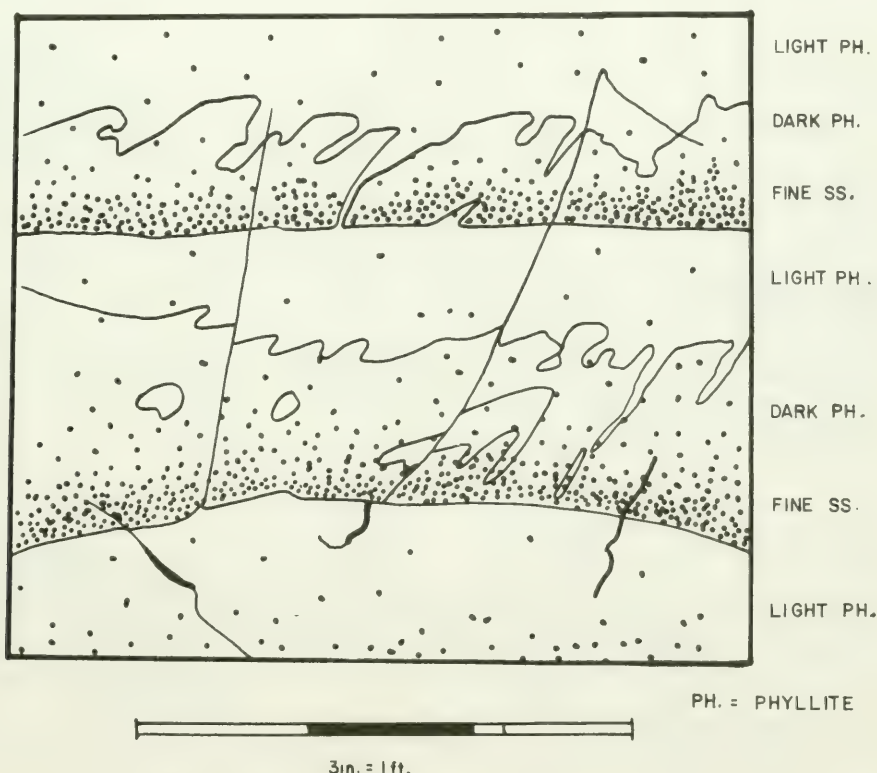
6 d - Sedimentary structures in unit d (station 6). The two stippled bands are dark gray phyllite that fine upward. The irregular upper margins of these bands may be worm burrows.

a   GREENISH GRAY PHYLLITE

b   DARK GRAY PHYLLITE

6 e - Refolded contact between units a and b along the west shore
      (Station 15). The hatches in the cross-section do not
      represent cleavage.
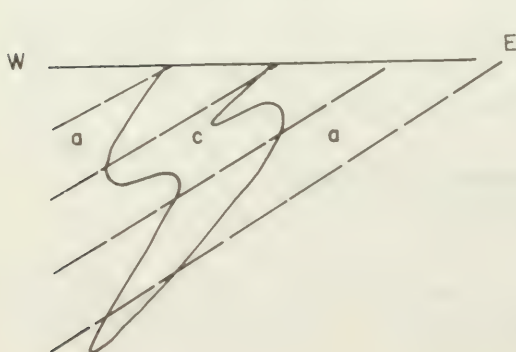
6 f - Folded contact between units
      a and c, along the line
      indicated in Figure 5
      (Station 16). Horizontal
      distance is approximately
      300 feet.

Return to Route 138, bearing left after crossing beach.

60.5   On return to Route 138 an historical windmill may be seen.

61.4   At Route 138 go left to Jamestown Bridge and continue to the end of
        Route 138.

62.1   East end of Jamestown Bridge, meta-sandstones of the Rhode Island
        Formation, forming a garnet-staurolite schist.

65.5   Road cut of staurolite-Kyanite schist, exhibiting festooned cross
        bedding which has been overturned.

66.4   On Route 138 follow signs for Westerly and New York to Routes 1
        and 138, and follow cloverleaf onto Route 138 and Route 1 South
        (Tower Hill Avenue).

73.4   Follow Route 1 to Narragansett Avenue (before 108); turn left and
        then an immediate left onto Peckham and park.

73.6(?) Stop 6 - Outcrop of migmatite in private yard.

        Stop 6 is in the yard of the house on the corner of Narragansett
        Avenue and Peckham (5 Peckham). Please obtain permission from the
        owner (Joseph Rankin) to look at this outcrop.

        The outcrop consists of alternating layers of leucosome (light
        colored layers) and melasome (dark-colored layers). The melasome is
        characterized by the assemblage, garnet - biotite- muscovite - quartz-
        plagioclase - microcline (Milne, 1972), and is relatively biotite-
        rich next to the leucosome. The melasome also contains veins that
        are complexly folded and are terminated by the leucosome, and has a
        well developed schistosity. The leucosome consists of variable amounts
        of quartz, feldspar, and biotite-rich schlieren. The lower part of
        the outcrop consists of a medium-grained, relatively homogeneous
        granite that cuts across the other two rock types. The light
        and dark layers are subparallel, although occasionally the leucosome cuts
        across the melasome. This migmatitic zone can be traced for at least
        several hundred yards, along strike.

        This outcrop or ones in the immediate vicinity have been considered
        to be among some of the best evidence of the intrusion of the Narragansett
        Pier granite into the Pennsylvanian metasediments (Nichols, 1956;
        Milne, 1972). However, the field relations are not compelling, and
        other origins are equally plausible. The witers would like to suggest
        an alternate as a working hypotheses. This explanation holds that the
        migmatite was formed by anatexis that accompanied the regional meta-
        morphism of the sediments, and that only the medium-grained homogene-
        ous granite may possibly be part of the Narragansett Pier. In support
        of this interpretation are the following observations:

        1. The general appearance of the migmatite suggests formation
        during regional deformation.

        2. The lack of chill zones in the leucosome indicates that
        the country rock was hot at the time of intrusion.

3. Away from the migmatitic zone, the melasome has a fine-sand layering that is complexly folded.

4. The unfossiliferous melasome is quite similar to a quartz-biotite schist of probably Precambrian age that occurs in the vicinity (Nichols, 1956).

5. This outcrop has been interpreted as a lit-par-lit zone (Nichols, 1956; Milne, 1972). However, despite its extensive development, there is no evidence of contact metamorphism of metasedimentary rocks in the area (Milne, 1972).

6. The Narragansett Pier granite has been dated as Pennsylvanian (or younger) in age. However, some of the gneissic border phases or it may in fact represent part of the basement. The report of an age of 343My for this granite (whole rock Rb/Sr; J. W. Barton, analyst) supports this interpretation.

7. The granitic material at this outcrop is more deformed than typical exposures of the Narragansett Pier granite. One of the writers (Hermes) plans to date the migmatite, and Pb^{207}/Pb^{206} ages on zircons from these rocks should be available by the time of the field trip.

In summary, the metasediments may actually be Pre-Pennsylvanian, and the granite may not be Narragansett Pier.

Return to Route 1; go right (north) and follow Routes 4 and 2 to I-95 back to Providence. Take I-95 to the Branch Avenue exit, Providence.

<u>Alternate Stop.</u> Directions to graphite mines.

Return to Route 1 (Tower Hill Avenue) and turn left

75.2 From Route 1 take Narragansett Exit and turn left off the exit ramp and go around rotary.

75.5 Following signs for Narragansett and Route 1A, exit from rotary at second right and proceed.

76.7 At second light turn left on Beach Street.

76.9 Left again at next light onto Bostoneck Road; continue for about four miles. The exact locations of the graphite mines may be obtained from Grew, 1974, Appendix 1.

Return to Bostoneck Road, turn left, and proceed to South Ferry Road, just beyond sign for U. R. I. Narragansett Bay Campus, turn left and follow South Ferry Road to Route 1. At Route 1 please follow preceding directions back to Providence.

105.9 Exit at Branch Avenue exit (Exit 24); go right to North Main and turn left, returning to Star Market.

106.5 <u>Stop 7</u>. Outcrop of Rhode Island Formation at University Heights, Providence, Rhode Island.
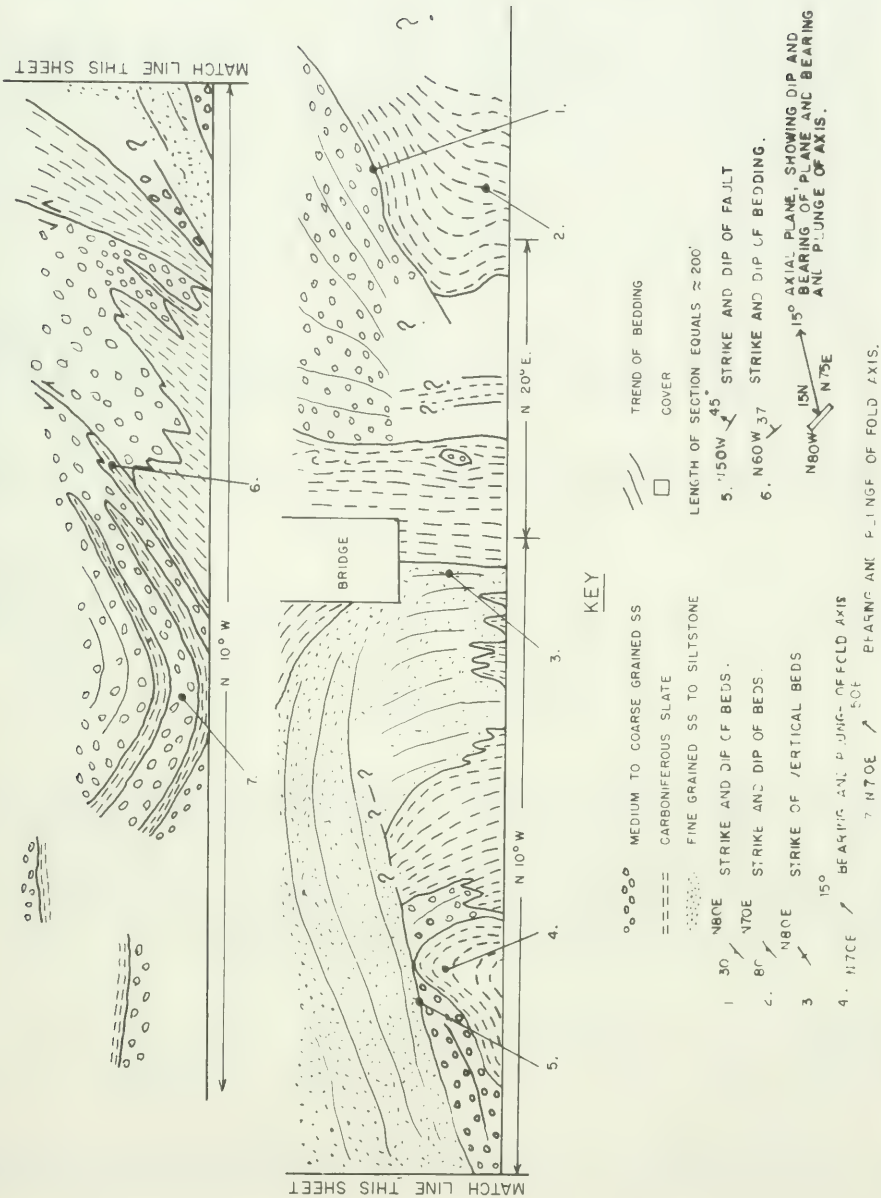
Figure 7. Sketch map of the geology along the hillside behind the University Heights Star Market, Providence, Rhode Island.

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The outcrop consists of interlayered mudstone and fine – to coarse – grained sandstone that has been folded and thrusted (Figure 7). Poorly developed graded bedding implies that the section is <u>not</u> overturned. For the northern two thirds of the outcrop, the general trend of the folding is to the east, and the direction of tectonic transport along the thrusts is to the south. The southern third of the outcrop also is folded and faulted; however, the fold axis trends N-S. The relationship of the two structurally divergent parts of the outcrops is not known, at present.

At this outcrop alternating layers of carbonaceous slate and coarse sandstone (to pebble conglomerate) are common, and decollement thrusting apparently is controlled by the ductility contrast between these two lithologies.

This outcrop occurs on the west limb of the N-S trending syncline that constitutes the Rhode Island portion of the Narragansett Basin. Note, however, that the general orientation of structures at this locale cannot be obviously related to this regional syncline.

General Note: Please obtain permission prior to visiting any out-crops located on private property.

ACKNOWLEDGMENTS

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Trip A-18
Mechanisms of Alleghenian Deformation in the Pennsylvanian

of Rhode Island

by

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Abstract

The Pennsylvanian conglomerates of Rhode Island probably afford the best demonstration in the published literature of rock deformation achieved by a pressure solution mechanism which has operated on a large scale. This excursion will visit numerous localities in various metamorphic grades and encompassing a variety of mean total strain values. It can be demonstrated that pebbles ranging in shape from highly prolate to appreciably oblate, have strain shapes that are almost exclusively the result of pressure solution. Abundant evidence of pebble-pebble penetration in directions of finite shortening and silica overgrowths in directions of finite extension demonstrate the effectiveness of pressure solution as a major deformation mechanism and permit some evaluation of the extent of volume changes during deformation

Introduction

The Narragansett Basin of southeastern Massachusetss and eastern Rhode Island is an arcuate structural basin, having a northeast-southwest trend in Massachusetts which deviates to a north-south trend in Rhode Island (figure 1). The basin is defined by the presence of up to 12,000 feet of Pennsylvanian age clastic sedimentary rocks of essentially non-marine origin. The basin is therefore structurally defined by the effects of Alleghenian deformation and its present shape may have an imprecise relationship to the Pennsylvanian sedimentary environment in which the rocks accumulated.

Conglomerates are present at numerous horizons within the Narragansett Basin, but the major occurrences are in the lower part and also near to the top of the Pennsylvanian sequence. The conglomerates occur in intermittent and discontinuous lenses up to several hundred feet in thickness and several miles in length.

Alleghenian deformation is most intense in the southernmost parts of the basin in Rhode Island, where the metamorphic grade ranges from the chlorite zone in the south-central part of the basin to above the level of the staurolite isograde in the southwestern extremity of the basin. Both the deformation and grade of metamorphism rapidly diminish northwards.
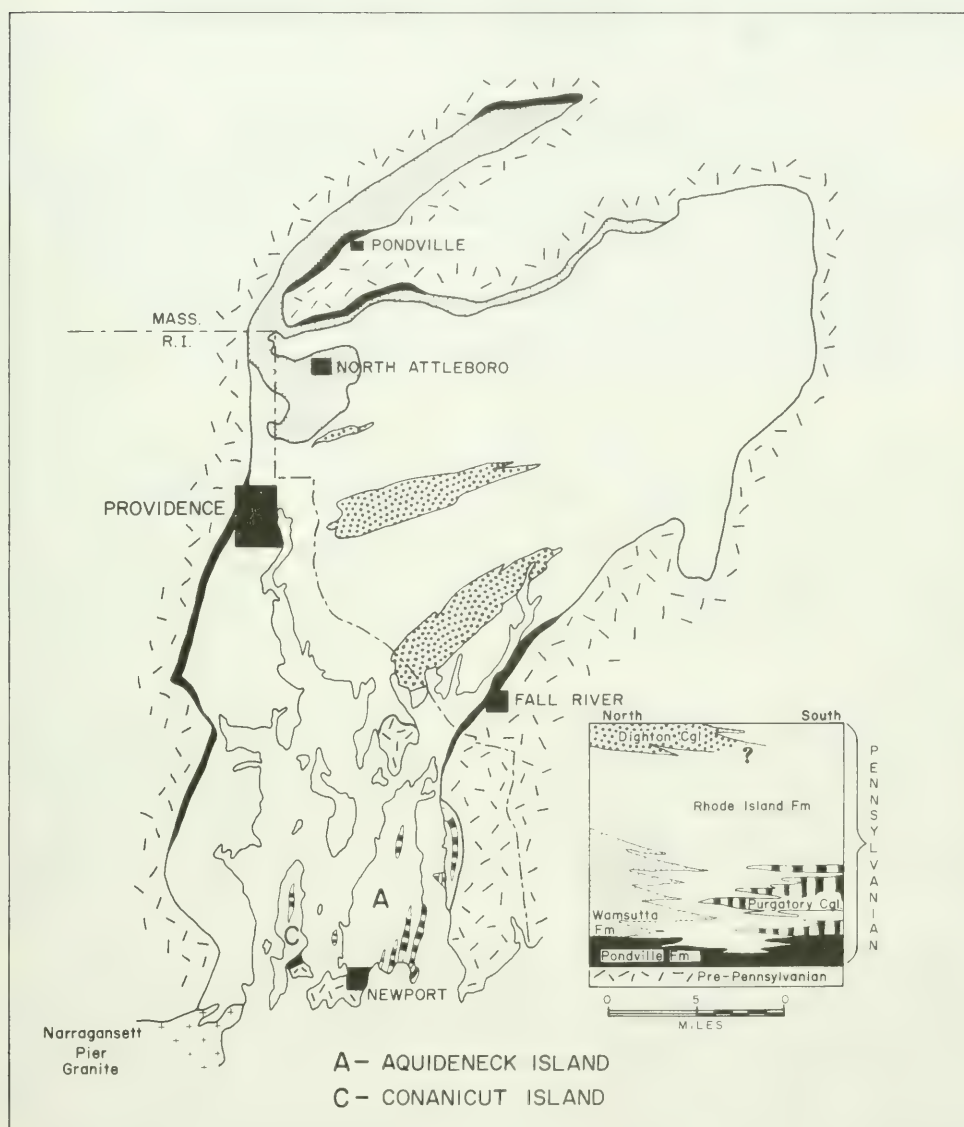
Figure 1. Geological sketch map and basic stratigraphy
of the Narragansett Basin.

The effects of Alleghenian deformation and the variation in its intensity are most spectacularly seen in the conglomeratic rocks of southern Rhode Island which are collectively known as the Purgatory Conglomerate.

Pre-Pennsylvanian Basement of Rhode Island

The basement is quite different on the two sides of the Narragansett Basin and no correlations are possible. To the east of the basin, the basement consists of the foliated Bulgarmarsh Granite which has a Lower Paleozoic age (Galloway, 1970), together with some low grade schists of sedimentary origin. The rocks on the western side of the basin include a highly heterogeneous assemblage of gneisses, foliated granites, and non-foliated granites, together with low to medium grade metasedimentary and metavolcanic sequences such as the Blackstone Series of northern Rhode Island.

The majority of the gneisses and granites to the west of the basin comprise the "Rhode Island Batholith". Although basically younger than the Blackstone Series (Quinn, 1971), this is a complex of crystalline basement which has undergone mobilization at several stages. The older part may pre-date the Blackstone Series which is itself intruded and partially granitized in places by younger mobilizates of Cambro-Ordovician age. The Hope Valley Alaskite and the Ten Rod Granite portions of the Rhode Island Batholith which were initially thought to be of Precambrian age (Day, 1968) have recently been revised to a somewhat younger age.

The Blackstone Series is totally unlike any known Lower Paleozoic rocks of the region and is considered to be of late Precambrian age. It consists of orthoquartzites, greywackes, siltstones, conglomerates, marbles, mafic to intermediate tuffs and mafic lavas which are, in places, pillowed. The main outcrop of the Blackstone Series passes under the Pennsylvanian rocks of the Narragansett Basin and almost certainly reappears as the pre-Pennsylvanian inliers at the south ends of Aquidneck and Conanicut Islands (figure 1).

Much of the Blackstone Series is in the highly disrupted form of a gigantic melange. Deformation is inadequate to account for the degree of disruption and work currently in progress by Robare, Wood and Mosher indicates that this may be a large submarine slide deposit. The presence of pillowed lavas, limestones and orthoquartzites within a sequence which is frequently in the condition of a melange is reminiscent of the late Precambrian of North Wales which has been correlated with the Avalonian of Newfoundland and other similar age events in the Appalachian region (Wood, 1974). This raises the possibility that the Blackstone Series may be equivalent to those late Precambrian formations of the Avalon Peninsula that underwent deformation and metamorphism immediately prior to 570 million years ago. It remains to be seen whether the Blackstone Series can be convincingly demonstrated either to be part of a plate margin sequence which accumulated at the edge of some pre-Iapetus ocean, or, whether it is the remains of an Avalonian age back arc basin.

Formation of the Narragansett Basin

There are three possible origins for the Narragansett Basin. It is either (a) a simple sedimentary basin which conformed essentially to the present structural basin; (b) a limnic graben; or (c) it may be a thrust sheet remnant. Weathering profiles observable at the southeastern contact with the basement, together with the presence of coarse, angular conglomerates near to the northern margin of the basin, appear to support the simple basin model. The graben model is a modification which would have the basin margins bounded by faults that may have been obliterated in places as they were covered by the latest Pennsylvanian sediments. This graben model would view the Narragansett Basin as being similar to the Hercynian grabens of southern Europe. The final possibility, that the rocks of the basin are part of an exotic thrust sheet, is the most speculative. However, new road cuttings in the western part of the basin along State Highway 138 (see figure 6) contain features reminiscent of those associated with the Honeyhill fault in eastern Connecticut where Alleghenian movement on this fault, along with thrusting on the Lake Char and Tatnic faults has been documented (Wintsch, 1975).

Pennsylvanian Stratigraphy of the Narragansett Basin

The basin contains approximately 12,000 feet of sedimentary rocks (Shaler et. al., 1899). Plant fossils indicate that much of the sequence is of Pennsylvanian age but it has been suggested that the entire sequence may range from upper Mississippian to Permian (Mutch, 1968).

The basic stratigraphy is shown in figure 1. The Rhode Island Formation may be considered as a matrix unit within which four other formations interfinger. These are the discontinuous and varied basal unit, the Pondville Formation; the overlying Wamsutta Formation and its approximate correlative, the Purgatory Conglomerate; and the highest preserved formation, the Dighton Conglomerate which is almost entirely restricted to Massachusetts and is only exposed between Fall River and North Attleboro. The Wamsutta Formation and Purgatory Conglomerate on the one hand, and the Dighton Conglomerate on the other hand, are separated by several thousand feet of the Rhode Island Formation.

The Pondville Formation is conglomeratic in the north and east of the basin; arkosic in the south of Conanicut Island; consists of well sorted interlayered sandstones and carbonaceous siltstones in the south of Aquidneck Island; and finally, along the eastern margin of the basin comprises a highly micaceous and somewhat carbonaceous arkose (Mutch, 1968).

The Wamsutta Formation is restricted to the northern part of the basin and consists of reddish siltstones and fine grey sandstones, together with coarser channel deposits. Volcanic detritus is widespread and both silicic and mafic lava flows occur near Attleboro.

The Purgatory Conglomerate occupies a similar stratigraphic position in the southern part of the basin to that of the Wamsutta Formation in the north. It is a coarse conglomerate composed primarily of quartzite boulders and pebbles. It outcrops east of the Sakonnet River near to the margin of

the basin, is very widespread on Aquidneck Island and also occurs in an
appreciably higher metamorphic grade on Conanicut Island. The conglomer-
ate occurs in elongate lenses ranging in thickness from a few feet to
several hundred feet. In most outcrops there is very little sand-size
matrix between the closely packed pebbles and boulders which owe their
cohesion almost entirely to tectonically induced pressure welding.

The Rhode Island Formation consists of nearly 10,000 feet of undif-
ferentiated sandstones, shales, thin conglomerates and some beds of meta-
anthracite (Quinn, 1971). Most of the formation appears to be of non-
marine, fluvial origin. The overlying Dighton Conglomerate may also be
of fluvial origin (Perkins, 1920).

The overall Pennsylvanian stratigraphy, with red beds and subaerial
volcanics (Wamsutta Formation) in the north, passing southwards into
coarse clastic sediments together with coals and shales (Rhode Island
Formation) and finally into a boulder conglomerate facies (Purgatory Con-
glomerate), would appear to indicate a southerly paleoslope in an environ-
ment of massive Pennsylvanian erosion and accompanying deposition. Swamps
and constantly fluctuating streams existed in what may have been a subsiding
and tilting basin or graben. The occurrence of the Purgatory Conglomerate
in the south of the basin may indicate that the basin opened in that direc-
tion (Mutch, 1968) into a uniformly higher energy environment in which the
coarse boulder units accumulated. One problem is the absence of marine
fossils in any of the sandy and silty units associated with the Purgatory
Conglomerate. Another problem is the source of the quartzite boulders.
The boulders are, on the basis of Walcott's recognition of fossils, Upper
Cambrian to Lower Ordovician in age (Walcott, 1898). Because some boulders
contain several species of the brachiopod Obolus which is also found in the
Lower Ordovician of Belle Island, Newfoundland, it has been suggested that
the source of the Purgatory Conglomerate was a southward extension of the
latter formation (Towe, 1959).

Alleghenian Structure and Metamorphism

The southern portion of the Narragansett Basin shows the principal
development of both deformation and metamorphism. Folding is on north-
south axes; axial surfaces are always steep; and the folds are upright to
overturned. There is no unique direction of fold vergence. The wavelengths
of major folds are commonly about one mile (Lahee, 1912), although wave-
lengths and amplitudes may reach a maximum of approximately five miles and
one mile respectively. Cleavage is commonly developed in argillaceous units.
There is frequently more than one cleavage. The principal cleavage shows
characteristically strong fanning and is only parallel to the axial surfaces
near to those surfaces. Elsewhere, this cleavage has undergone modifica-
tion in orientation as a result of slip along contrasted lithological boun-
daries subsequent to its initial formation. A somewhat random orientation
of later cleavages about the fold axes, is similarly explained by localized
shear within individual beds as a result of slip along their bounding sur-
faces. The deformation reaches its maximum expression in the Purgatory
Conglomerate.

In the southern part of the Narragansett Basin, the lowest grade of metamorphism is that of the chlorite zone which encompasses most of Aquidneck Island. Eastward the grade increases into the biotite zone; westward it is locally sufficient for staurolite to occur. Sillimanite has been recorded in the disused graphite mine at Tower Hill, approximately one and a half miles north of Narragansett Pier in the extreme southwest of the basin. Staurolite is found on Conanicut Island, below the eastern end of the Jamestown Bridge, where it occurs in a quartz-free, muscovite-rich rock which contains garnet and graphite. The staurolite bearing units are interbedded with graphitic shales containing clearly recognizable plant fossils. The occurrence of both sillimanite and staurolite may be a chemical anomaly or be related to the possibility that a high level, short lived metamorphism held the rocks at a high temperature for a period that was insufficient for complete equilibrium to be attained.

The lower grade rocks clearly show that an initial syntectonic progressive metamorphism was followed by a stage of late-tectonic retrogressive metamorphism during which static growth of both biotite and garnet occurred.

The metamorphism has been ascribed to the intrusion of the Narragansett Pier Granite (figure 1) which does indeed intrude Pennsylvanian metasediments in the extreme southwest of the basin. However, the granite becomes more pegmetitic rather than aphanitic towards the Pennsylvanian contact in most places. Furthermore, the granite appears to be quite inadequate in extent to account for the metamorphism. Some twenty miles to the north of the Narragansett Pier Granite, the Pennsylvanian contains regionally developed garnet in an area where the pre-Pennsylvanian basement consists of the Blackstone Series. It is therefore more likely that the Narragansett Pier Granite represents the southern part of the pre-Pennsylvanian Rhode Island Batholith that underwent local Upper Paleozoic metamorphism and partial remobilization.

Conglomerate Deformation in Southern Rhode Island

The Purgatory Conglomerate occurs in a series of elongate north-south ridges which mark the positions of major fold limbs. Dips are commonly steep and range from 50° to 80°. Conglomerate units are interbedded with thin sandstones and magnetite-rich sandstone lenses. Pebbles in the conglomerates are predominantly quartzite, although rare granite and schist pebbles are present. The conglomerates are seen in metamorphic grades ranging from chlorite to garnet.

The pebbles and boulders generally have the form of triaxial ellipsoids, but vary from highly prolate to appreciably oblate throughout the basin. In places, for example on Coaster's Harbor Island (locality 5), they are relatively undeformed. It has been shown that the major part of the deformation in that part of the basin which is in the chlorite grade, was achieved by a pressure solution mechanism (Mosher, 1976). Interpenetration of adjacent pebbles (figure 2), together with the widespread development of pressure-shadow overgrowths of fibrous quartz on the long-axis terminations of pebbles (figure 3), both testify to the effectiveness of the pressure solution mechanism. Where pebble-pebble contacts occur, the internal fabric of both pebbles is totally devoid of any penetrative deformation and any internal bedding
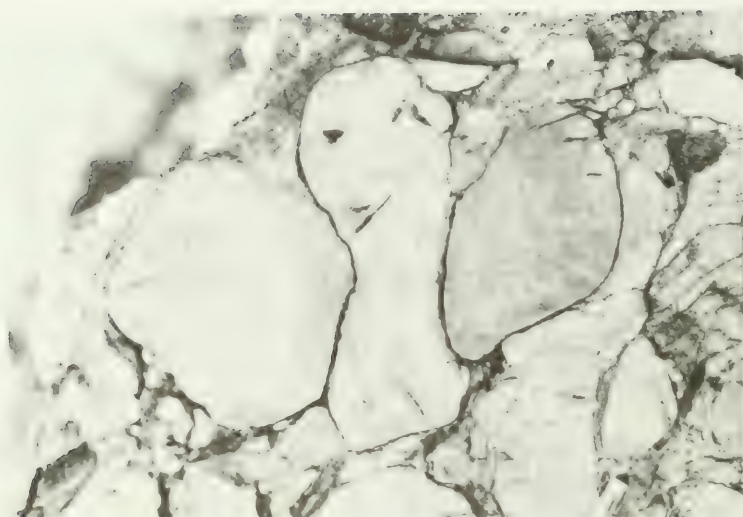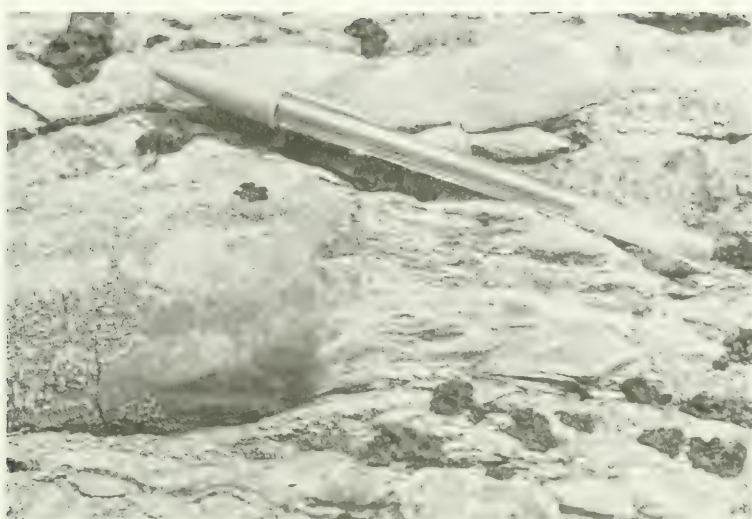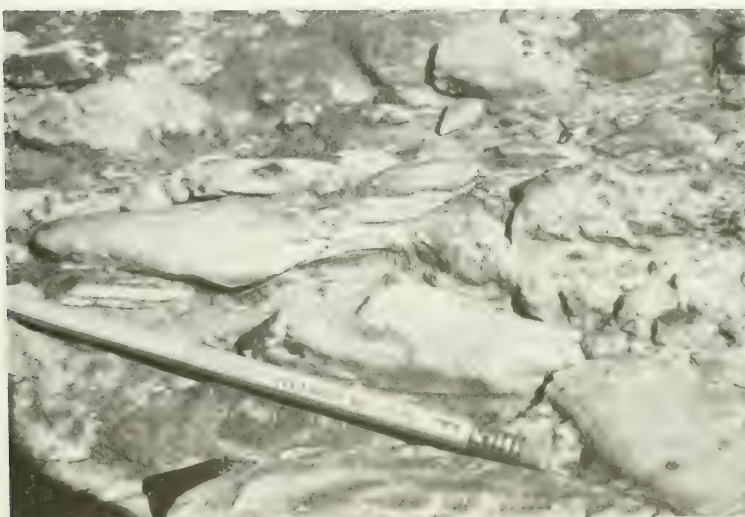
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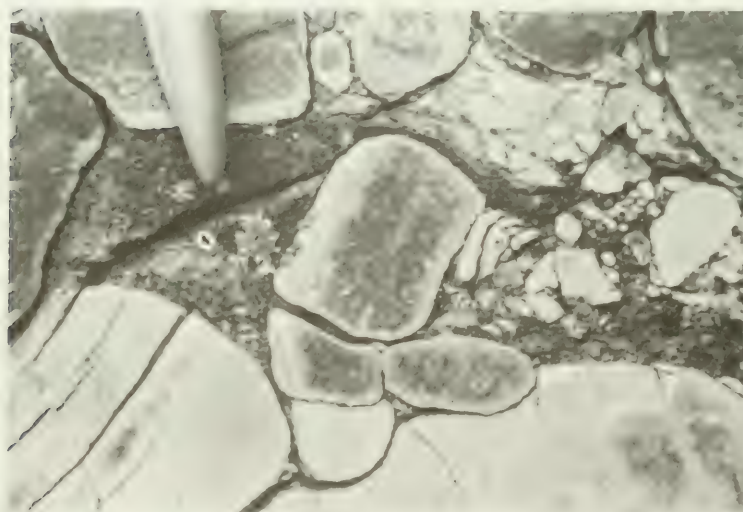
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Figure 2.   Quartzite pebble inter-penetration features:
A. Mutual interpenetration of pebbles. Pebble
      margins conform perfectly, with both of any
      adjacent pebbles showing volume loss.
B. Small pebbles indenting a larger pebble.

A

B

Figure 3. Fibrous pressure shadows of nearly pure quartz:
A. Overgrowth at the long axis termination
of an elongate quartzite pebble.
B. Overgrowths connecting two quartzite pebbles.

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remains undistorted. Although the amount of strain, as indicated by the pebble shapes, varies, as also does the degree of metamorphism, continuing work indicates that pressure solution is a most important factor in the deformation of the entire basin.

The amount of deformation which has taken place at various localities can be represented in several ways. Standard deformation plots of log X/Y against log Z/Y are shown in figure 4 for the first two localities to be visited. Their most striking feature is the wide scatter of individual pebble shapes. Although some of the scatter is due to an initial shape factor effect, it is the pattern to be expected in a conglomerate where pebble shapes have been modified by pressure solution. In such a case, the pebbles will not undergo uniform dissolution but, rather, this will depend upon their position relative to other pebbles, size, degree of solubility and amount of inter-pebble matrix.

A more satisfactory means of demonstrating the amount of shape change undergone by pebbles is shown in figure 5 where the pebble ratios Y/X and Z/X are plotted. The reason for using this plot is that pebbles are indented and pitted in every direction normal to their long axis which itself has undergone no change in length. This latter is demonstrated by the fact that fibrous quartz overgrowths are restricted to long-axis terminations of pebbles. Thus the long pebble dimension (X) remains unaltered, whereas every direction in the plane containing the Y and Z axes is one of finite shortening. In this special case, where the pebble shapes can be reasonably plotted as in figure 5, the magnitudes of shortening in the Y (intermediate) and Z (short) axis directions can be read directly as principal strains. Thus, for locality 2 (west side of Sakonnet River) the average shortening of Y is 49% and of Z is 67%. The average "principal strains" for the pebbles, rather than the bulk rock, are therefore: $E_1 = 0$; $E_2 = -0.49$; $E_3 = -0.67$. For locality 1 (High Hill Point on the east side of the Sakonnet River), the average principal strains are $E_1 = 0$; $E_2 = -0.52$; $E_3 = -0.75$.

Even if initial shape fluctuations are taken into account, the data presented in figure 5 indicates that enormous volumes of silica have been removed from pebbles. This was either redeposited as pebble overgrowths and matrix or a certain amount may have been removed from the system. If shape factors are ignored, an average of more than 80% of the initial pebble volume has been removed and redistributed. Even if shape factors are considered, the average volume loss per pebble has been in excess of 50%, which is itself appreciably higher than the usual volume changes during deformation (Ramsay and Wood, 1973).

It is thought that the conglomerates in question were initially unlithified boulder beds poor in matrix support, became sorted into a closer packing by initial deformational movements, and underwent extreme pressure solution modification of their shapes and accompanying deposition of a cementing siliceous matrix. The result of this extensive pressure solution has been to permit major large scale shape change of the Purgatory Conglomerate rock body.
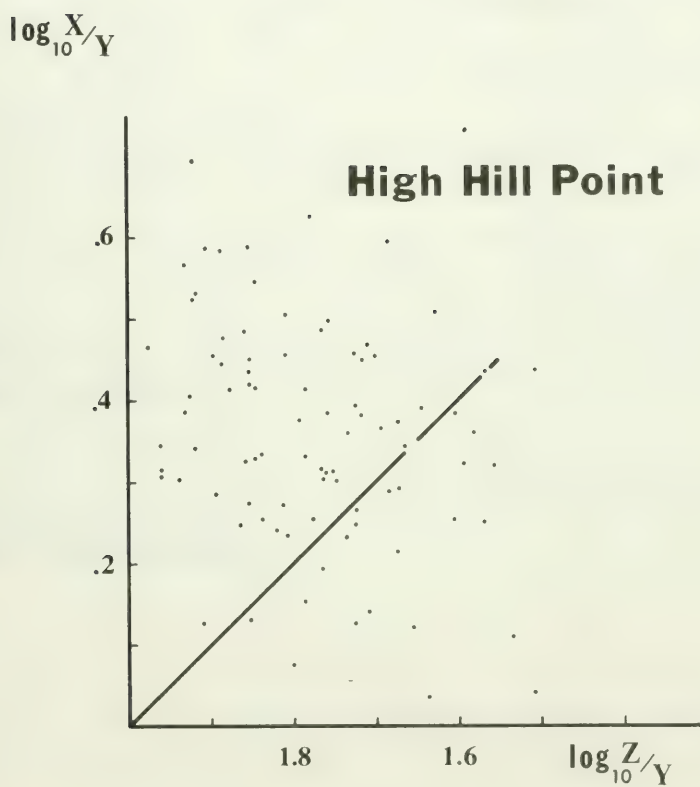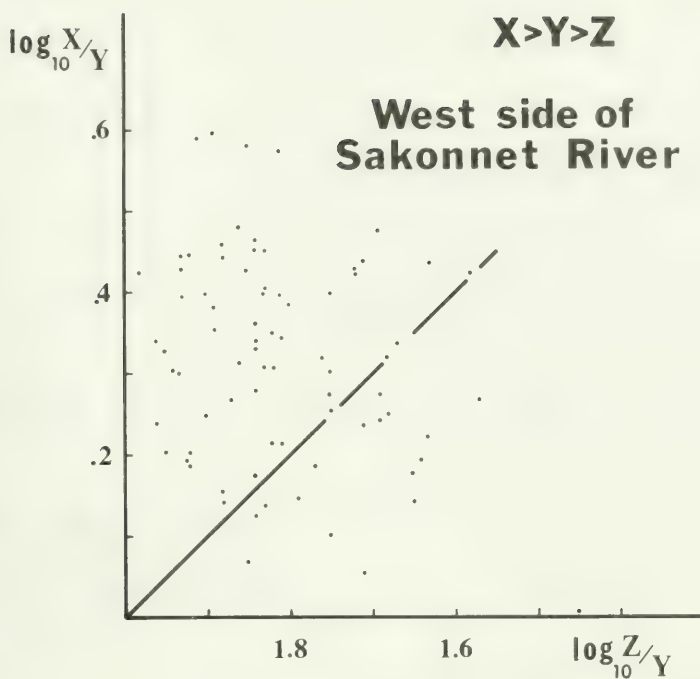
Figure 4. Deformation plots for two localities. The large scatter demonstrates the non-uniform character of pressure solution deformation.
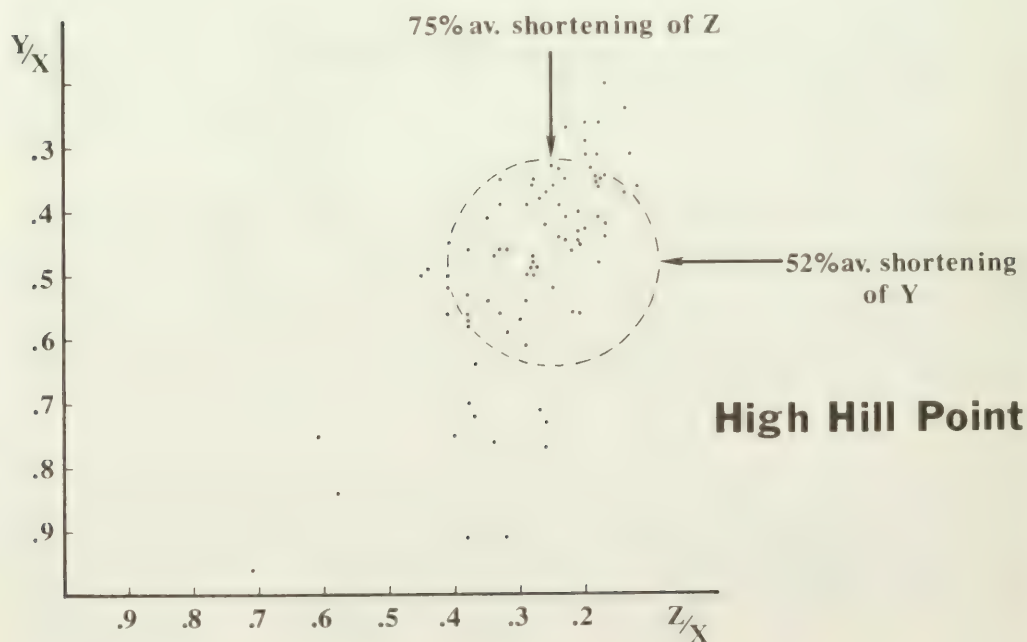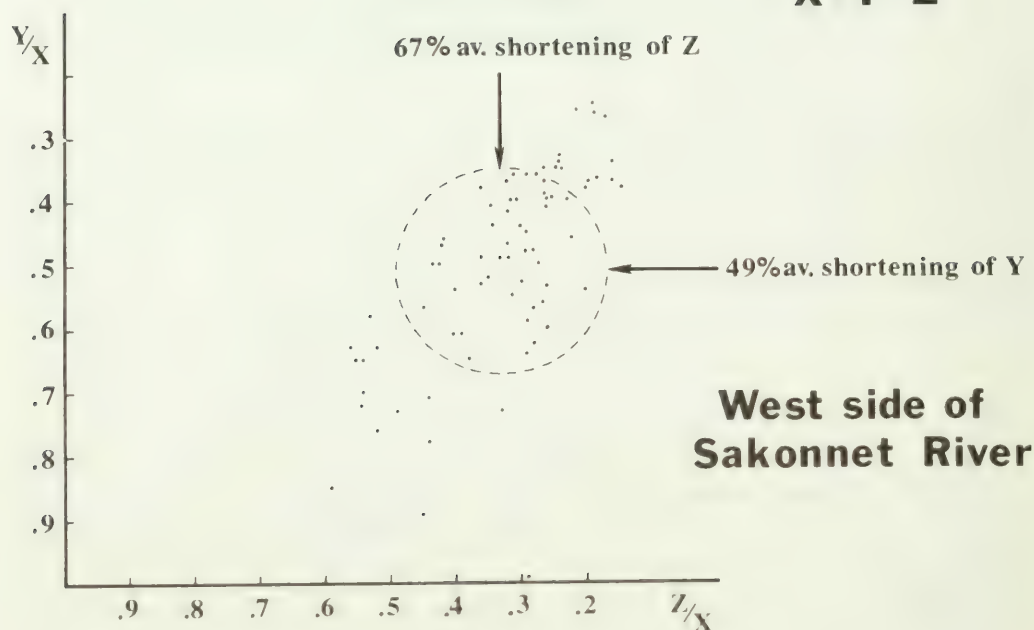
Figure 5. Deformation plots for the special case where the long axis of the deformation ellipsoid remains unchanged. The two localities are the same as in Figure 4.

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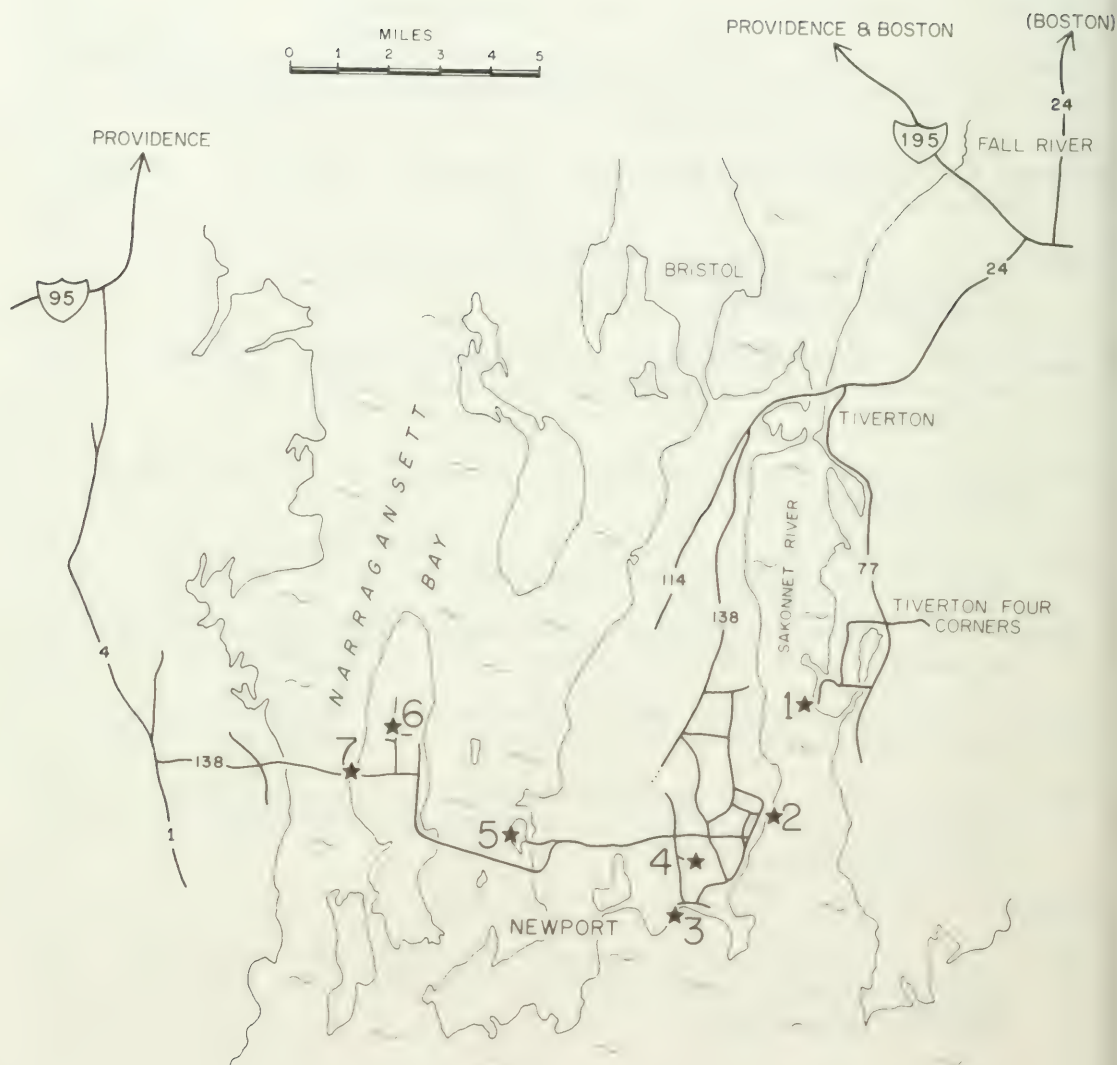   Early Caledonian subduction in Wales. S.E.P.M. Special Publication
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Figure 6. Road map of southern Rhode Island showing stop locations.

Road log

Meeting Place: Parking lot of Gray's Ice Cream Drive-in at Tiverton Four
      Corners (intersection of route 179 and route 77), four miles south of
      Tiverton on route 77.

From Boston: Take route 3 south to route 128 west. Follow route 128 to
      route 24 south. Turn off of route 24 at the exit for route 77 south
      to Tiverton. Follow route 77 to the meeting place. Figure 6 indicates
      all necessary roads and the stop locations.

      (The outcrops along the interchange of route 24 and route 77 are of
      basement rocks - Bulgarmarsh granite - which are at the margin of the
      Narragansett Basin. All of the exposure seen on route 77 from Tiver-
      ton to the meeting place is of basin sediments.)

mileage

0.0 Gray's Ice Cream Drive-in. Continue south on route 77. The road is
      now on basement rocks.

1.4 Turn right on Fogland road - second road on the right - will cross a
      bridge 0.15 miles along the road. This road crosses into the basin
      and the rocks are of the Rhode Island formation.

2.0 Turn left at T intersection and then immediately right - Go Slow!

2.5 Note the tombolo to the right. The island is composed of Purgatory
      conglomerate. Follow the road as it turns left.

3.0 Turn right into parking lot.

      Stop 1. High Hill Point. This stop provides an excellent opportunity
      to observe the Purgatory conglomerate in three approximately perpendi-
      cular directions in the biotite metamorphic zone. On horizontal sur-
      faces the long axes of the pebbles exhibit perfect alignment trending
      $N15^{O}E$; joint faces roughly perpendicular to the long axes of the
      pebbles show an even better alignment of the intermediate axes. The
      long and intermediate axes lie in a plane dipping 38° SE. Bedding
      strikes $N15^{O}E$ and has dips varying from 12° to 24° SE.
         Pebbles are over 90% quartzite with the remainder granite and
      schist. All have an extremely flattened and elongated fabric. Inspec-
      tion of the pebble surfaces indicates that most of this flattening is
      due to numerous large indentations from the adjacent pebbles. At the
      long axis terminations of the pebbles fibrous quartz pressure shadows
      are prevalent. It is therefore suggested that the pebbles were
      deformed by pressure solution, and the majority of the shape change
      can be accounted for by a reduction in volume of the pebbles. A few
      shear fractures can be observed which enhance the flattening effect
      of the pressure solution. The High Hill Point portions of figures 4
      and 5 were compiled from measurements taken at this site. Average
      shortening in the Y direction is 52% and 75% in the Z direction. (See

text for further discussion.)

Return to route 77 via the same route.

4.6   Turn left and proceed north.

6.7   The road now follows a long outcrop of Purgatory conglomerate. Note
      patches of conglomerate in yards for the next 1.5 miles. The ridge
      0.5 miles to the right is the Bulgarmarsh granite.

7.2   Behind the houses to the left is a large ridge of conglomerate which
      contains a lense composed mostly of granite particles from the nearby
      basement rocks.

8.5   Sutherlands Restaurant. In the small parking lot beneath the building
      and along the road to the right are outcrops of conglomerate. Beds
      here are almost vertical and long pebble axes roughly trend N45°E and
      plunge 68° NE.

11.6 Follow signs for route 24 (route 138) south to Newport.

12.0 Cross bridge. Observable outcrops are of an up-faulted block of
      Metacom granite (basement rock).

15.3 Take route 138 exit and continue south.

20.0 Turn left on Sandy Point road.

20.5 Turn right on Wapping road (first right).

22.5 Turn left on Old Mill lane. Note outcrop of conglomerate. Pebbles
      are aligned N10°E with bedding striking N15°E and dipping 22° SE.

23.3 Turn right onto Indian avenue.

23.5 Turn left on second small road - before the large V-shaped buildings
      on the right. Park in the circle at the end of the road.

23.6 Stop 2. This stop is on the west side of the Sakonnet River, south-
      west of the first stop. The pebbles at this stop are very similar to
      those at the previous stop. The long axes trend N8°E and the inter-
      mediate and long axes lie in a plane dipping 30°-40° SE. As shown by
      figure 5, these pebbles also show a highly elongated and flattened
      fabric, but are slightly more prolate than those of the first stop.
      The average shortening in the Y direction is 49% and is 67% in the
      Z direction. The pressure solution deformation mechanism is again
      suggested (fig. 4). The composition of the pebbles and the abundance
      and effect of the shear fractures are comparable to those of the last
      stop.
            The bedding in this area strikes approximately N10°E and has
      been reported to have dips of 70° SE (Lahee, 1912) to an overturned
      83° SE (Quinn, 1971). At this site many beds are near vertical and
      dip towards the NW. However, some adjacent sand lenses dip 50°-65°SE.

The bedding orientation is also complicated by a fault which cuts across the outcrop running roughly parallel to the strike of the bedding.

Return to Indian avenue.

23.7 Turn left. The road crosses into chlorite grade metamorphic rocks.

25.7 Intersection of Indian avenue, Third Beach road and Hanging Rock road. Continue straight on Hanging Rock road.

26.3 The ridge to the right is the southern end of one of the longest continuous exposures of conglomerate. It is one of the best out-crops available for demonstrating the pressure solution features. This is part of the Norman Bird Sanctuary; access is ONLY through the main gate situated 0.6 miles north on Third Beach road. From there it is possible to walk from the Rhode Island formation into the conglomerate and along the top of the ridge to Hanging Rock. It is well worth a visit, but obey all of the rules. The area is well patroled.
    Bedding strikes N10°E and dips 65°NW. The long and intermediate axes lie in a plane dipping 40°-55°NW; long axes trend N18°E.

26.5 Turn right onto Second Beach road.

27.0 Park in parking lot on left.

Stop 3. Lunch stop. For the best view of both rocks and scenery, walk up the outcrops on the left to the top of the ridge near Purga-tory Chasm. NO HAMMERS - this is a state park. After lunch, meet at the Chasm.

Purgatory Chasm. This is the classical outcrop commonly used to demonstrate the nature of this 'stretched' pebble conglomerate. It has been shown, however, by both microscopic and field relations that these pebbles have been deformed primarily by pressure solution - not stretched (Mosher, 1976). The pebbles seem to be more prolate than previous stops with long axes trending N10°E; only an ill-defined sub-vertical alignment of the plane containing the long and intermedi-ate axes exists. Bedding varies slightly, but on an average, strikes N10°E and dips 55°SE. This exposure extends beyond the boundary of the park both to the south where it is cut by numerous vertical EW joints exposing large rock faces and to the north on the other side of the road. Stop 4 is a northern continuation of this outcrop.
    The pebbles have tangential, almost planar, and deeply embayed contacts (figs. 2,3). Thinsections of these contacts show no evidence of quartz and mica deformation in either pebble; internal pebble bedding shows no distortion at such contacts. Large fibrous pressure shadows of quartz can be seen at the long axes terminations of most pebbles (figs. 4,5). Because of the glacially scoured surfaces, another important feature can be observed at this locality. The matrix between the pebbles ranges from less than 1 mm to 3 cm thick. Where the pebbles are in close contact, the matrix is depleted in

quartz and enriched in both micaceous components and heavy minerals. In such zones the quartz content is usually much less than 10%. In contrast, the quartz of the matrix near to long axis terminations commonly amounts to 95% by volume. The latter zones are pressure shadows whereas the thin micaceous seams between closely adjacent pebbles is considered to be residual material remaining after pressure solution.

The pebbles are predominately quartzite with rare granite and few schist pebbles. The latter are easily mistaken for matrix. Careful observation can detect a boundary between the pebble and the matrix, however. Occasionally the schist pebbles are surrounded by small quartzite pebbles. Many shear fractures are observable with offsets enhancing the elongation of the pebble. At the top of the hill near the small parking lot for the Chasm, matrix beds grade into the Rhode Island formation proper. These show cross-bedding and both a flat-lying and steep cleavage.

Take Paradise avenue north. (Turn left out of parking lot and right off Second Beach road.)

27.9   Turn right to Paradise Quarry.

28.3   Park in lot.

Stop 4. Paradise Quarry. This is primarily a collecting stop since most others are no hammer stops. Pebbles with good indentations and pressure shadows are easy to find. This locality is a continuation of the ridge at Purgatory Chasm.

Return to Paradise avenue.

28.7   Turn right and proceed north.

29.2   Turn left on Green End road: continue straight for several miles.

30.4   On the right are some small exposures of conglomerate. This is the southern end of Miantonomi Memorial Park. The sides of the hill surrounding the memorial tower show good exposure of the conglomerate. Down slope to the west are outcrops of disputed Pondville conglomerate which may or may not be in place.

30.8   Rotary. Go 180° and continue in the same direction toward Coaster's Harbor Island Naval Base.

31.4   Naval Base main gate. Wait for permission. Follow lead car around circular drive past the hospital to War College.

31.8   Turn left and drive behind buildings; park.

31.9   Stop 5. Coaster's Harbor Island. Pebbles are a jumbled mass of all shapes and sizes. Their surfaces are rough in comparison with the pebble surfaces at the previous stops. A high degree of fracturing

is observed which appears to be a late occurrence, and small high angle faults are also found. A few pitted pebbles and 'micro'-pressure shadows are present. The amount of matrix is greater than at other localities. The bedding strikes N55°E and dips 20°NE; the pebbles have a slight alignment trending N17°E and plunging 30°NE. Although quartzite is again predominate, there is an increase in the amounts of granite and schist pebbles over the last stop.

32.0   When leaving parking lot, turn left and immediately right onto another main road. The outcrops on the right are of conglomerate.

32.3   Turn right - second road.

32.6   Turn left and return to Rotary.

33.1   Rotary - take it 180° and slowly continue straight.

33.2   Take route 138 exit to the Newport Bridge to New York and Jamestown. Tokens for the toll are in your folder. Cross bridge.

35.5   Pay toll. Continue straight on route 138 past interchanges.

36.7   Turn left following route 138.

37.2   Turn right on North Main road.

38.3   Turn left and park on the side of the road.

Stop 6. Garnet grade metamorphism has effected the conglomerate of this outcrop. Garnets are found in the matrix between the pebbles and are pressure-solved into the pebbles themselves. This indicates that pressure solution continued after the culmination of the retro-gressive metamorphism. Pitted pebbles and pressure shadows are common; long axes of pebbles trend N8°E, and intermediate and long axes lie in a plane which dips 32° SE. Bedding strikes N6°E and dips 76°SE. The pebbles are mainly quartzite, but the amounts of shale and granite pebbles is somewhat greater than at the last stop.

Return to route 138.

39.4   Turn right.

40.3   Turn right and park along the side of Seaside Drive.

Stop 7. Jamestown Bridge. Carbonaceous staurolite-garnet schists, which are muscovite-rich and quartz-poor, alternate with graphitic shales containing perfectly recognizable plant fossils. Small lenses of deformed pebbles are present.

Continue west on route 138 across the Jamestown Bridge.

42.1   Note the outcrops in the road cuts.

42.3 Continue on route 138.

43.7 Again note outcrops in the road cuts. These two outcrops show
      possible features associated with thrusting.

44.3. Take exit for route 4 north to Providence. Continue on route 4
      until I95. Go north on I95 through Providence to route 128. Take
      that east to route 3 north to Boston.

THE EFFECT OF URBANIZATION ON WATER QUALITY

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I. Introduction and Purpose

In his forward to the Circular 601 Series, Hendricks (1969) states in part, "Urbanization -- the concentration of people in urban areas and the consequent expansion of these areas -- is characteristic of our time. It has brought with it a host of new or aggravated problems that often make new demands on our natural resources and our physical environment. Problems involving water as a vital resource and a powerful environmental agent are among the most critical." This trip will examine the Charles River, a river which well illustrates Hendricks' concern. The Charles rises in a rural setting but almost immediately flows through an urban area and the effect of this passage on the quality of the water is marked. The river continues on its course through both urban and rural settings, ending in an artificially impounded area termed the Charles Basin. The basin, an area greatly modified by man, serves as a sink for various forms of effluent from the densely populated urban areas of Boston and Cambridge. This trip will examine the quality of water at several points along the Charles River and explanations for the level of water quality encountered will be offered. Several field testing kits will be available for use and the results obtained from them will be charted and discussed.

II. Description of the Watershed

The Charles River watershed is an elongated, hourglass shaped area approximately thirty miles long and five to fifteen miles wide comprising 307 square miles. The source of the Charles is a spring flowing from Honey Hill in Hopkinton (see map, figure 1). Runoff from this spring flows into Echo Lake which is generally considered to be the headwater of the river. The watershed varies in elevation from 586 feet above mean sea level along the south westerly divide in Hopkinton to less than 10 feet along its lower reaches. The river is almost 80 miles in length and falls a distance of 350 feet from Echo Lake to the Charles Basin where the water surface if normally maintained at 2+ feet. The gradients of the various river reaches are controlled by the approximately twenty-two dam locations spaced at irregular intervals along the river. The western and northern parts of the watershed are moderately hilly while the eastern and southern areas are characterized by more rolling topography and extensive swampy areas. Marsh and wetlands make up about one tenth or 20,000 acres of the watershed.
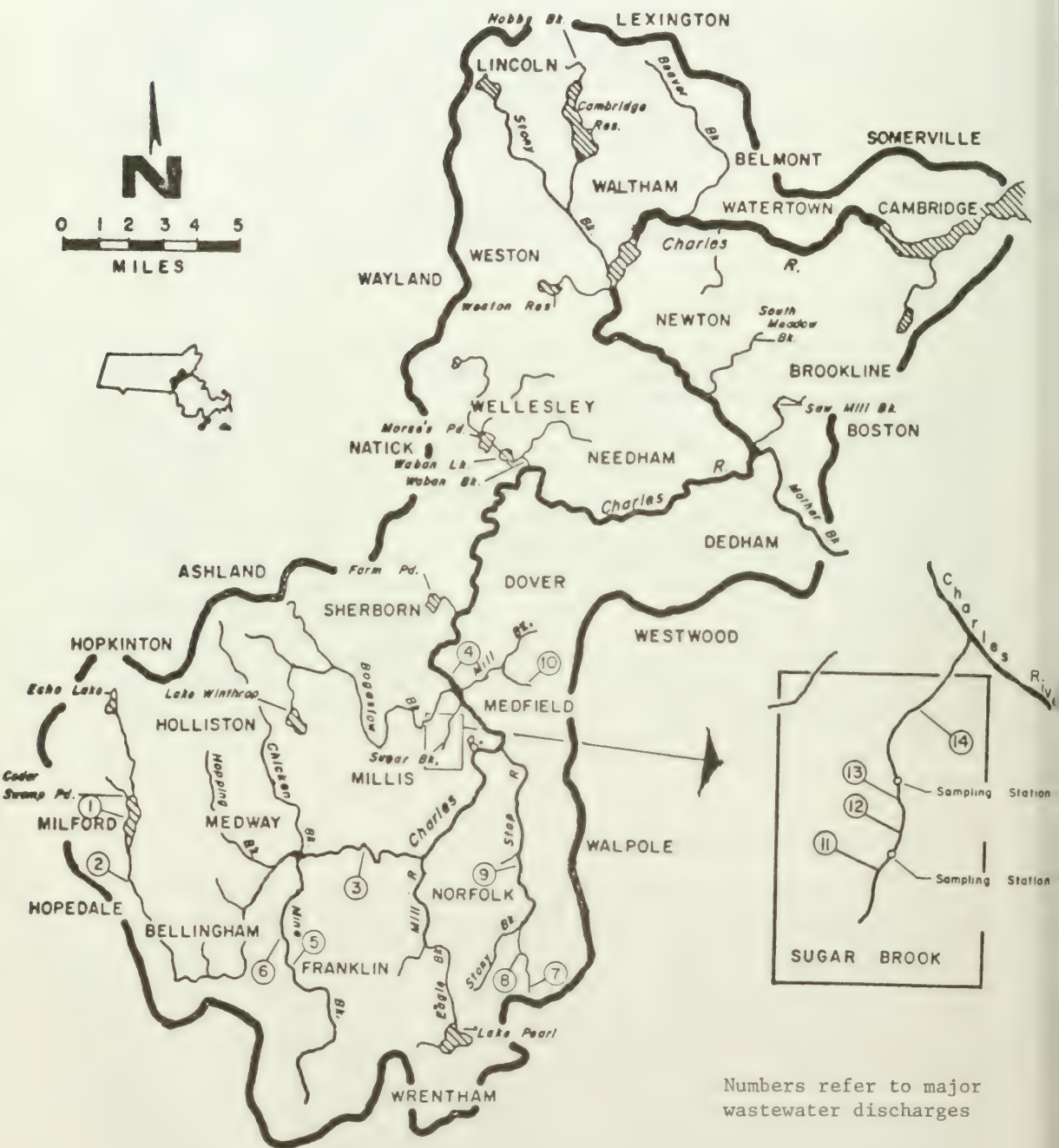
Numbers refer to major
wastewater discharges

(after Massachusetts Water
Resources Commission, 1974)

Figure 1

The climate is humid temperate with an average annual temperature of 49°F, and an average annual precipitation of 44 inches distributed evenly over the year. Discharge data recorded at 4 U.S.G.S. gaging stations within the watershed are as follows:

Location of Gaging Station	Drainage Area (sq. mi.)	Period of Record	Discharge (cfs)		
			Mean	Maximum	Minimum*
Charles River at Charles River Village, Mass.	184	1937-1969	292	3,220	0.9
Mother Brook at Dedham, Mass.	--	1931-1969	77	1,040	0
Charles River at Wellesley, Mass.	211	1959-1969	312	2,410	1.0
Charles River at Waltham, Mass.	227**	1931-1969	368	2,670	0.2

*Minimum daily
**Excludes 23.6 square miles drained by Stony Brook

The Charles River flows through the most highly populated watershed in Massachusetts. The 1970 population was in excess of 810,000 persons with the highest densities (13,000 - 14,000 per mile in Boston and Cambridge) in the highly developed urban areas of the lower watershed. The Charles River flows over bedrock of pre-Paleozoic to Mesozoic age which is mantled by unconsolidated glacial drift. The upper tributaries generally are underlain by older formations while upper Paleozoic rocks are found under the lower reaches of the river. The river generally flows in till and on bedrock in its upper reaches and in unconsolidated glaciomarine and outwash sediments in the middle and lower reaches. The course of the river is controlled in great measure by the pattern of the surficial sediments overlying the bedrock. Frimpter (1973) shows the location of several thin, irregular shaped deposits of sand and gravel serving as ground-water reserves in the watershed and the influence these have on the course of the river is well illustrated.

III. Water Quality

Urbanization, in one form or another, has dominated the Charles River ever since man began to settle permanently near it. During the initial colonization of the river in the period 1630-1675, twelve settlements were built along 75 miles of the 80 mile river, and we haven't stopped since. The watershed is now outlined by interstate expressways I-495, I-90, and I-95. State highways liberally crisscross the area. These transportation routes link up the 35 communities which lie wholly or partially in the watershed. That degradation

of the Charles River is occuring due to this urban growth is obvious, and one of the best ways to measure this degradation and its intensity, is by determining the quality of the water. Some of the standard water quality parameters and their definitions are given below. (Definitions are taken from Massachusetts Water Resources Commission, 1976, and Cragwell, 1975.)

Biochemical Oxygen Demand (BOD) - The amount of oxygen required by bacteria to stabilize organic matter. BOD consists of two parts, carbonaceous and nitrogenous. The carbonaceous portion occurs first; compounds of carbon are broken down with the carbon released combining with oxygen to form carbon dioxide. In the nitrogenous portion, organic compounds of nitrogen are broken down to ammonia which in turn is converted to hydrogen gas and, successively, nitrite and nitrate. Although the total BOD of a waste may take 30 days or more to exert itself, the portion exerted after 5 days has become the standard test through recurrent usage. The 5 day BOD of untreated sewage normally ranges from 150 to 300 mg/1. Streams not subject to pollution will normally have 5 day BOD's of 2.0 mg/1 or less.

Coliform Bacteria - Found in abundance in the intestinal tract of warmblooded animals. Although not harmful themselves, the presence of coliforms often indicates that pathogenic bacteria are also present. Since they can be detected by relatively simple test procedures, coliforms are used to indicate the extent of bacterial pollution. Tests are often conducted to measure the total and fecal coliform. Fecal coliform make up about 90 per cent of the coliforms in fecal matter. Non-fecal coliform may originate in soil, grain, or decaying vegetation. Untreated sewage contains upwards of 20,000,000 coliforms per 100 milliliters. The legal maximum for swimming areas is 1000 coliform per 100 ml, while for public water supplies it is 100 per 100 ml.

Color - In water analysis the term "color" refers to the appearance of water that is free from suspended solids. Many turbid waters that appear yellow, red, or brown when viewed in the stream show very little color after the suspended matter has been removed. The yellow-to-brown color of some waters is usually caused by organic matter extracted from leaves, roots, and other organic substances in the ground. In some areas objectionable color in water results from industrial wastes and sewage. Clear deep water may appear blue as the result of a scattering of sunlight by the water molecules. Water for domestic use and some industrial uses should be free from any perceptible color. A color less than 15 units generally passes unnoticed. Some swamp waters have natural color in excess of 300 units.

Dissolved Oxygen (DO) - The uncombined oxygen in water which is available to aquatic life; DO is therefore the critical parameter for fish propagation. Numerous factors influence DO, including organic wastes, bottom deposits, stream hydraulic characteristics, nutrients, and aquatic organisms. Saturation DO, or the equilibrium concentration, is primarily a function of temperature. DO values in excess of saturation are usually the result of algal blooms and therefore indicate an upset in the ecological balance. Optimum DO values range from 6.0 mg/1 (minimum allowable for cold water fisheries) to saturation values. The latter range from 14.6 mg/1 at

0°C (32°F) to 6.6 mg/l at 40°C (104°F).

Dissolved solids - Theoretically, dissolved solids are anhydrous residues of the dissolved substances in water. All solutes affect the chemical and physical properties of the water and result in an osmotic pressure. Water with several thousand mg/l of dissolved solids is generally not palatable, although those accustomed to highly mineralized water may complain that less concentrated water tastes flat. The U.S. Public Health Service recommends that the maximum concentration of dissolved solids not exceed 500 mg/l in drinking and culinary water on carriers subject to Federal quarantine regulations, but permits 1,000 mg/l if no better water is available.

Hardness - Hardness is the characteristic of water that receives the most attention in industrial and domestic use. It is commonly recognized by the increased quantity of soap required to produce lather. The use of hard water is also objectionable because it contributes to the formation of scale in boilers, water heaters, radiators, and pipes, with the resultant decrease in rate of heat transfer, possibility of boiler failure, and loss of flow. Generally, bicarbonate and carbonate determine the proportions of "carbonate" hardness of water. Carbonate hardness is the amount of hardness chemically equivalent to the amount of bicarbonate and carbonate in solution. Carbonate hardness is approximately equal to the amount of hardness that is removed from water by boiling. Noncarbonate hardness is the difference between the hardness calculated from the total amount of calcium and magnesium in solution and the carbonate hardness. The scale formed at high temperatures by the evaporation of water containing noncarbonate hardness commonly is tough, heat resistant, and difficult to remove.

Hardness range (calcium carbonate in mg/l)	Hardness description
0-60	Soft
61-120	Moderately hard
121-180	Hard
More than 180	Very hard

Ammonia-Nitrogen - Nitrogen in the form of dissolved ammonia gas (NH_3) or ammonium ion (NH_4^+). Concentrations over one or two mg/l are toxic to certain fish and other aquatic organisms. Nitrification of ammonia by bacteria to nitrite and nitrate exerts a biochemical oxygen demand. Ammonia is also a nutrient for algae and other aquatic plants.

Nitrate-Nitrogen - Nitrogen in the form of dissolved nitrate ion (NO_3^-). Nitrate is a primary nutrient for algae and other aquatic plants.

Total Kjeldahl-Nitrogen (Total Kjeldahl-N) - The sum of ammonia-nitrogen and nitrogen in all organic forms (which may include living cell matter). Bacterial decomposition of organic forms rapidly produces ammonia-nitrogen, perhaps resulting in toxic ammonia concentrations.

pH - A measure of the hydrogen ion concentration of a solution on an inverse

logarithmic scale ranging from 0 to 14. Values from 0 to 6.9 indicate acidic solutions, while values from 7.1 to 14 indicate alkaline solutions. A pH of 7.0 indicates a neutral solution. Natural streams usually show pH values between 6.5 and 7.5, although higher and lower values may be caused by natural conditions. Low pH values may result from the presence of heavy metals from acid mine drainage or metal finishing waste. High pH values may result from detergents or limestone quarrying.

Specific conductance (micromhos per centimetre at 25°C) - Specific conductance is a convenient, rapid determination used to estimate the amount of dissolved solids in water. It is a measure of the ability of water to transmit a small electrical current.   The more dissolved solids in water that can transmit electricity the greater the specific conductance of the water. Commonly, the amount of dissolved solids (in mg/1) is about 65 percent of the specific conductance (in micromhos).

Temperature - Temperature is an important factor in properly determining the quality of water. This is very evident for such a direct use as an industrial coolant. Temperature is also important, but perhaps not so evident, for its indirect influence upon aquatic biota, concentrations of dissolved gases, and distribution of chemical solutes in lakes and reservoirs as a consequence of thermal stratification and variation.

Total Phosphorus (Total P) - The sum total of phosphorus in all forms in which it may be present, including dissolved and particulate, organic and inorganic, in living cells and, most importantly, in the form of dissolved phosphate ion ($PO_4^=$). Phosphate is a primary nutrient for algae and other aquatic plants.

Turbidity - Turbidity is the optical property of a suspension with reference to the extent to which the penetration of light is inhibited by the presence of insoluble material. Turbidity is a function of both the concentration and particle size of the suspended material. It is reported in terms of mg/1 of silica or Jackson turbidity units (JTU).

Sources of pollution along the Charles include point sources such as municipal sewers and sewage treatment plants, institutional discharges from hospitals and prisons, and industrial discharges. Fourteen major point sources have been identified in the watershed upstream from the Watertown Dam. These are located in figure 1. Other point sources are sewer overflows and bypasses, disposals of sewage sludge, and discharges of cooling water. Non point sources include urban runoff, subsurface disposal (cesspool and septic tank leakage), the effect of dams, leachate from sanitary landfills, wetland discharge, agricultural practices (fertilizers), and mining.

IV. Field Trip Schedule

A formal road log will be available for distribution at the Conference. The morning schedule will focus on the upper part of the watershed, especially from the source of the Charles down to below the town of Milford. There are some very interesting dynamics present in the rise and fall of dissolved

oxygen and BOD levels due to the impact of the town of Milford. Lunch will be at a location in the middle part of the watershed. It will probably not be practical to buy food on the way so be sure to bring a lunch. The afternoon will be spent in and around the lower part of the river in the portion below the Watertown Dam known as the Charles Basin. This is by far the most highly polluted part of the river. It is "fed" by an intricate network of streams, outfalls, and sewage overflows. The layer of sludge on the bottom of the basin will be discussed and sampling will endeaver to show the layered nature of the waters in the Charles Basin.

The entire river is included on the following U.S.G.S. Massachusetts topographic quadrangles:

Boston South	Holliston
Newton	Franklin
Natick	Blackstone
Medfield	Milford

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_____ 1976, The Charles River, part d.

ENGINEERING GEOLOGY OF THE CHARLES RIVER

by

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Introduction

The new Charles River Dam will be a multi-purpose project with provisions for flood control, recreational and commercial navigation, and future highway transportation. It is located in the Boston inner harbor on the site of the defunct Warren Avenue Bridge, linking Boston and Charlestown. The project will include an earth dam, three navigation locks, a pumping station, provisions for a future highway viaduct, an overhead enclosed walkway, fish ladder and sluice gates. It will provide flood control by maintaining the basin at a constant elevation above sea level and prevent a recurrence of the damages of the record flood of August, 1955, which resulted in losses of $5.5 million ($21.3 million under present economic conditions).

The dominating project feature is the large pumping station which is approximately 190 feet long, 85 feet wide and 60 feet high. This building will house 6 pumps capable of discharging 630,000 gallons per minute each. Each pump is driven by a 3,000 horsepower diesel engine. Offices, personnel rooms, work shops, control rooms and public viewing areas overlooking the engines and navigation locks are also located on the Boston Harbor side of the pumping station. The 400-foot long walkway connects the pumping station with the navigation locks and an MDC police building, located at the Boston end. The walkway contains control consoles for operation of the navigation lock gates. The two recreation navigation locks are 200 feet long and 22 feet wide. The large commercial lock is 40 feet wide and 300 feet long.

The design and construction of the project is under the supervision of the U. S. Army Corps of Engineers in cooperation with the Metropolitan District Commission of Massachusetts who will operate and maintain the new dam. The project was designed by the Architect-Engineer firm of CE Maguire, Inc., Waltham, Mass. Estimated cost of the new dam is $41 million of which the Metropolitan District Commission will contribute $8.7 million which includes utility relocations and real estate costs. The MDC will also construct a pollution control facility in the upstream river estuary at a cost of approximately $15 million. This will include a sewage detention and chlorination station and extension of the Boston marginal sewer conduit to tidewater beyond the new dam.

A construction contract in the amount of $34,957,257 was awarded to J. F. White Contracting Co. in February, 1974. This is the largest individual construction contract in the history of the New England Division. Completion of the project is scheduled for December, 1977.

Geology and Soils

Site Geology

General - The damsite is located on the Charles River, a tidal estuary to Boston Inner Harbor. The area is part of the Boston Lowland and once consisted of mainly tidal flats and salt marshes that have been progressively reclaimed and filled since Colonial days so that present shorelines are well beyond their former positions. The Lowland is part of the Boston Basin, a structural synclinal basin occupied by rocks of Carboniferous age consisting of siltstone, slate, conglomerate and volcanics. The Cambridge Slate occurs in the site area. The "slate" is generally fine-grained and composed chiefly of argillaceous material, usually massive rather than slaty and therefore better termed an "argillite". In some areas in the Boston Basin, the argillite may be altered to a clay-like consistency to significant depths. Recent marine deposits of organic silt, mud and peat overlay the glacial deposits and in turn are extensively overlain in some areas by manmade fills. The subsurface picture is generally depicted on Plate 2-16 of the hand-outs.

Subsurface Exploration - Test borings (32) were made in 1948 for the rebuilding of the Warren Avenue bridge and are on or applicable to the dam site as are to a lesser degree about 20 borings made in 1950-51 for the Central Artery bridge located just upstream of the site. In 1963, 74 borings were made for the Metropolitan District Commission on a grid pattern of 75 feet except where prevented by existing structures. The MDC borings and previous borings were of standard penetration type common to explorations made in the Boston area. These borings were sampled at 5-foot intervals using a 24-inch split spoon of 1-3/8 inches I.D. driven by a 140 pound drop weight falling 30 inches. Borings were taken to refusal and at a few locations refusals were established as bedrock by coring.

In 1970, the New England Division made 12 borings, FD-1 to FD-12, to further delineate the surface of the glacial till, and established bedrock by coring refusals in 4 of the borings, FD-1, 2, 3, and 6. These borings were made using a solid 5-foot sample spoon of 2 inches or 1-1/2 inches I.D. driven by a 300 pound or 350 pound drop weight falling about 18 inches. Additionally, a 6-inch diameter boring was made to recover undisturbed samples for testing of the organic silt stratum which will remain in the foundation for portions of the earth embankments and temporary construction slopes. A plan of explorations is shown on Plate 2-16 of the hand-outs. Graphic logs of selected borings are shown on Plate 2-17 of the hand-outs.

Foundation Conditions

General - Feature foundation designs will be covered in pertinent portions of forthcoming design memoranda, "Embankments and Foundations", "Navigation Locks and Facilities", "Pumping Station", amd "Vehicular Viaduct."

Foundations - The dam will extend across the Charles River estuary which is about 500 feet wide at the project site. The structures for the navigation locks and the pumping station will be founded in or on dense glacial till overlying bedrock. The glacial till consists of compact gravelly clayey sand and gravelly sandy clay with occasional cobbles and boulders. Density tests on drive sample plugs indicate that the dry unit weight of the till ranges from 130 to 145 p.c.f. In portions of some of the recent borings, it was possible to recover samples of the till by the rock-coring method. The Boston Building Code allows a bearing value of 10 tons per square foot on "hardpan" or till and this value may be exceeded by 5% for each foot of additional depth, not exceeding three times the initial bearing value.

The vehicular viaduct approach piers will be on piles. The piles will extend through man-made fills and organic silt into glacial till or to bedrock. The earth embankment portions of the dam are located at both abutment reaches. On the Boston shore, the embankment forms part of the vehicular viaduct approach fill. The selection of embankment height and width are dictated by geometric highway requirements. The fills will consist of granular material and the embankment will have necessary slope protection.

Seismicity - The Boston area is placed in the category of high risk rating (Zone 3) according to the seismic risk map recently developed by the Environmental Sciences Service Administration and the Coastal and Geodetic Survey. This rating implies that major damage could occur in Boston and apparently stems mainly from the severe earthquakes of 1727 and 1755. These quakes have been assigned on the basis of damages and accounts, intensities of IX with aftershocks of intensities up to VI according to the Modified Mercalli scale. Damage at the high intensity would be considerable even in specially designed structures. Earthquake damage is usually greater in structures founded on loose or soft soils than on bedrock. As discussed under "Foundations", all concrete and steel structures will be well founded on or in dense glacial till underlain by bedrock. According to Engineering Technical Letter No. 1110-2-109, 21 October 1970, hydraulic structures in Zone 3 will be designed to withstand earthquake acceleration of .10g.

Construction Materials

Materials for embankment fills and stone for slope protection will be contractor furnished except for use of acceptable materials from required excavations. Concrete aggregate from three competitive sources in the Boston area have been tested and reported in the Design Memorandum No. 3, "Concrete Materials."

The Field Trip

The field trip will consist of an inspection of the second stage cofferdam excavation at the Charles River Dam Project in Boston. The purpose of the dam is to replace the old lock system which controls the water level in the upper Charles and prevents salt water intrusion. A review will be made of the geologic considerations affecting the design and construction of the project structures. This will be followed by a tour of the site of work which will allow an inspection of the exposed foundation conditions. Additional information and diagrams will be handed out to participants at the time of the trip.

ASPECTS OF THE ECONOMIC GEOLOGY OF

SOUTHEASTERN MASSACHUSETTS

by

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Masslite Division of the Plainville Corporation Plant & Quarry

Since 1962 Masslite has produced lightweight aggregate (LWA) from expandable shale beds in the Rhode Island Formation (Pennsylvanian) of the Narragansett Basin where it joins the Norfolk Basin. Exposures are predominently sandstone or siltstone with lesser amounts of carbonaceous shale and a few conglomerate or conglomerate sandstone beds. Scattered throughout the sequence are fossil ferns and other plants distorted during folding. Interbedded with the carbonaceous shales is an interval of 10 to 15 feet of graphitic coal. Some of the shale beds contain "nodules" with associated pyrite. The LWA is produced from these carbonaceous shales. The Rhode Island formation strikes approximately N. 35°E. and is tightly folded and faulted. Displacements are difficult to determine due to the lack of repetition of key beds. Some of the interbedded shales show a crude axial plane cleavage oriented N. 35°E. 80°SE.

The shale is fragmented by drilling and blasting at the quarry face, loaded by power shovel into Euclid trucks, hauled to the plant and stock piled. Oversize material (> 36") is broken in the quarry by a dropped ball. Material from the stockpiles is transported by frontend loader to one of two hoppers feeding primary jaw crushers. These crushers are capable of accommodating particles up to 36" in diameter. At the crushers, raw material from different sections of the quarry is blended with coal from the quarry. As the local coal is a high ash, low BTU variety, additional coal (from Pennsylvania) is added to it to achieve proper burning characteristics. Quartz sandstone or siltstone is also added to the shale in order to temper it. Mix ratios have been determined by laboratory analysis of bloating characteristics, specific gravity, sintering characteristics etc. but they are presently approximated by experienced personnel.

The discharge from the primary crushers (minus 6") is passed through a double deck vibrating screen. The coarse rejects (plus 3") are recycled through a gyratory crusher and the fine rejects (minus 3", plus ½") are recycled through two gyratory crushers. Discharge from these secondary crushers is ¼" or less and it is conveyed to stockpiles. The stockpiled raw material is transported to hoppers by frontend loaders, where it is blended with waste clinkers from the furnace.

Material from the hoppers is fed by conveyor to a surge bin feeding the traveling grate in the furnace. The furnace, approximately 8' by 10', is an overhead oil burner which ignites the shale-coal mixture and initiates the bloating of the LWA. As the coal burns, temperatures of approximately 2200°F. are reached during sintering. The firing time and temperature are varied so as to accommodate the variations in composition and texture of the feed material. During firing, the shale is rapidly heated to a state of incipient fusion. At this temperature, the shale becomes a viscous liquid and simultaneously produced gases serve to expand the shale. Most of the gas (CO_2) is produced by the oxidation of the included carbonized plant fossils. In addition, the oxidation of sulfur is another source of gas; where pyrite is present. The expanded shale leaves as a sintered blanket of lightweight aggregate and it is broken by rotary knives, cooled rapidly, and discharged. The furnace exhaust is collected and passed through cyclones and discharged.

The furnace discharge (clinker) is transported by frontend loader to a hopper where it is conveyed to a hammer mill. The mill discharge (minus ½") is conveyed to a double deck vibrating screen where it is sized into 3 product sizes (3/8", 1/4", and minus 1/4").

The product L.W.A. ("popcorn") is used in the manufacture of cinder blocks and lightweight concrete. In addition, a new product, Agreg, is being produced as a landscaping soil cover and for soil conditioner. Present plant capacity is 600 tons per day of lightweight aggregate. Masslite L.W.A. is shipped throughout southern New England and as far as New York City by rail.

Masslite also produces aggregate from overlying sandstone beds exposed in another section of the quarry. The sandstone is broken and run through the jaw and gyratory crushers following which it is sized into selected fractions according to require specifications and stockpiled. The fines are passed through a spiral hydroclassifier and stockpiled while the overflow is piped to settling basins.

General Geologic Setting of the Clay Deposits in the Bridgewater-Middleboro area

A layer of glacial sediments of Wisconsin age covers essentially all of the Bridgewater Quadrangle. These deposits consist of ground moraine, glacio-lacustrine deposits and glaciofluvial deposits. A thin layer of aeolian sand covers some of the area.

Glacio-lacustrine deposits occur throughout much of the quadrangle predominating on both sides of the Taunton River. The glacio-lacustrine deposits are clayey silts and are blue-grey in color, drying to a light grey. Maximum thickness of the silts exceeds 100 feet. The silts were deposited in a pro-glacial lake which acted as a settling basin for the fine size particles. The varved silts suggest a seasonal or climatic control of deposition.

Individual "yearly" varves vary in thickness from a maximum of about 4 feet to a minimum thickness of a fraction of an inch. It is common for larger varves to contain thinner (diurnal?) couplets. Drop stones are scattered occasionally throughout the silts along with occasional pyritic nodules and carbonized wood. The clay beds vary somewhat in thickness laterally, and the thicker beds show intraformational convolutions and what appear to be slump structures. At the Stiles & Hart Pit, cross bedding and climbing ripples were observed but the outcrop is presently under water. The clays are overlain by 5-10 feet of thinly bedded sands and silts that grade vertically to more massive and coarser sand layers.

The Stiles & Hart Brick Company

The stiles & Hart Brick Company is family owned with operations in Bridgewater, Massachusetts.

The clay raw material is removed from a pit by a shovel or drag line and transported by truck to the processing plant a few hundred yards from the pit. It is dumped into a bin where an augur mixes the clay, removes boulders and passes the clay onto a conveyer belt where it is passed through a sand molding machine. The company is currently making a few hand-molded water struck bricks also.

After the clay is molded into bricks it is loaded onto mobil drying racks and dried for a period of 36 hours at a temperature of about 180°F. During this time considerable moisture is lost and shrinking of the brick occurs. Care must be taken in this process to produce even drying, eliminating cracking of the bricks.

After drying the bricks are loaded onto palates and placed in a bottom fired bee hive kiln where they are baked at about 1900°F. for 98-140 hours. The bricks are then allowed to cool and are removed from the kiln on the palates. They are taken to the storage yards and prepared for shipment by truck or rail to their customers.

The Kelsey-Ferguson Brick Company

The Kelsey-Ferguson Brick Company is a wholly owned subsidiary of The Susquehanna Corporation manufacturing a complete line of quality face brick. This operation had the most modern manufacturing facilities on the continent as of 1971. The brick being manufactured from local clay on the property. Production capacity is approximately 40 million bricks per year.

Manufacturing of brick is by Stiff Mud Extrusion and consists of 5 stages.

Mining: The clay pit is located approximately a quarter of a mile behind the plant. They are presently mining to a depth of 50 feet. Drilling data shows the clay to be at least 100' thick, although at the plant site it thins to almost zero. There is an estimated 100 year supply of clay at present rates of consumption. The clay is mined with a three yard dragline and loaded into a 30 ton dump truck. At the plant the clay is stockpiled under cover.

Drying: When the clay is mined, it contains a very high percentage of
moisture averaging between 20 and 30 percent. As the clay cannot be
worked satisfactorily with such a high water content it is dried in
a continuous rotary dryer to approximately 14% H_2O. A shuttle
conveyor spreads and blends the clay at this stage to insure a uniform
brick in the later stages.

Grinding: The dry clay is transported by a $2\frac{1}{2}$ yard front end loader to a
storage bin. Clay is fed automatically through 3 roll grinders in
series. As the clay enters the grinders, coloring oxides, barium
carbonate or other additives are added. The ground clay then enters a
surge bin.

Brick Production: The ground clay (with additives) is fed from the surge
bin to a pugmill where control water is automatically added to bring
the moisture content up to 16%. As plasticity is extremely important
in the extrusion of brick, the moisture content is a critical factor.
The pugged mixture is discharged by a screw auger, sliced by a rotary
knife and dropped into a vacuum chamber. The chamber is under a 27
inch vacuum and as the clay enters, entrapped air bubbles are removed.
This results in more workable plastic clay that has a higher green
strength. The clay is forced form the vacuum chamber by a screw auger
through a die and wire cut to the desired thickness. At this time a
surface texture and/or color can be applied as required. The extruded
bricks are then conveyed to and stacked on a kiln car.

Drying & Firing: The stacked bricks are transported on the kiln car to a
36 car capacity, twin-track, tunnel dryer. Waste heat generated by
the cooling of finished bricks is recirculated and used to maintain an
air temperature of about 300°F. in the dryer. The hot moist air is
exhausted at a temperature of about 125°F. Drying time is about $2\frac{1}{2}$ days.
    Following drying the cars are transferred to a 420' long, top-
fired, tunnel kiln and fired at 1950°F. Transit time for a kiln car
is approximately $2\frac{1}{2}$ days and the kiln is operated 24 hours a day seven
days a week.
    The initial stage of firing is accomplished with a high rate of air
circulation to bring the bricks up to a uniform temperature, to
oxidize any carbon or pyrite and release chemically combined water.
At approximately 1100°F. the inversion of α -quartz to β-quartz is
accomplished with a concomitant increase in volume.
    In the second stage of firing, the bricks go through a fast
shrinkage state as the clay structure is destroyed. Continued heating
results in the vitrification of the clay and formation of the brick.
    The final stage is cooling and this is controlled to prevent thermal
shock due to the volume change accompanying the inversion of β-quartz
to α-quartz at about 1100°F. The rapid volume decrease (thermal shock)
tends to cause cracked bricks that are useless as structural elements.
As the bricks reach 125°F. they are discharged, graded and packaged
for shipment.

Comparison Brick Production Chart

Company Name	Stiles & Hart	Kelsey-Ferguson
Ownership	family	corporation
Projected Production	20 million, 1976	40 million, 1976
Sales area	Mass. & R.I. Max. distance-Missouri	Most of the N.E. states
Transportation	Mostly truck-some rail	All truck
Type of brick	Decorative architectural facing brick	High quality facing brick
Method of brick production	Machine - sand molded. A few hand molded	Extruded - wire cut
Production per day	70,000 approximately	125,000 approximately
Percent loss	3% stable	Variable - 5%
No. of employees	45	about 50
Degree of mechanization	Partially mechanized	Highly mechanized
Total time to produce brick	$12\frac{1}{2}$ - $14\frac{1}{2}$ days 1 day mold & prepare for dryer $1\frac{1}{2}$ days to dry 2 days load kiln 4-6 days cook 2 days cool 2 days unload $12\frac{1}{2}$-$14\frac{1}{2}$ total days	6 - 7 days 1 day extrude 2 days to dry 2 days kiln 1 day cool 1 day packaging 7 days total days
Type of kiln	Bee hive kiln	Tunnel kiln
Type of fuel	Oil fired	Oil fired
Method of loading kiln	Fork lift-$1\frac{1}{2}$ days	Mechanized loading
Method of coloring brick	Flashing method	Flashing & spray method
Drying time & temp.	36 hrs./180°F.	48 hrs./300°F.
Baking temperature and time	1880° - 2000°F. 98-140 hours	1900° - 1940°F. 36-48 hours in kiln
Type of furnace	Bottom fired	Top fired
Additives	None	$BaCO_3$ & 40% ground shale
Disintegrator	No	Yes

Eastern Quarries, Inc., Weymouth, Mass.

The Eastern Quarries, Inc. are suppliers of high quality seamface and splitface granite. (Thomas C. Michaud.)

The quarries are located in the "Weymouth granite", an informal designation for a uniform, medium to fine grained light gray granite which has been mapped as a phase of the Dedham granodiorite. In the quarry, deleterious characteristics are generally knots or xenoliths and basaltic dikes. However, they are sufficiently rare so as not to constitute a major problem. Sulphides seem to be present in trace amounts and may be the source of the ubiquitous iron stained joints in the granite.

Surface iron staining, which is generally a very undesirable characteristic, is strongly developed in some sections of the quarry. This iron stain is in fact a very desirable feature of these quarries. Sap (stained) rock has been widely used in major construction in the northeastern United States and as far away as Illinois. The sap rock is quarried in areas where there are either closely spaced sheet structures or closely spaced vertical to steeply dipping joint sets. The irregular distribution of the best grade material has resulted in the development of numerous scattered pits of varying sizes and depths in the area of the present operations.

This stop should afford us the opportunity to witness a dying art – stone cutting. Large joint slabs are broken loose from the quarry and transported to the work sheds. Very large slabs have to be split to manageable proportions. These slabs are first drilled with a maul and star drill. They are then split by inserting feather wedges. The more manageable pieces can then be cut by chisel into either dimension or facing stone. As thickness, grade, and color vary it is perhaps best to record a general price range for the granite. Prices range from approximately $30 to $75 per ton.

The stonecutters are all middle aged and lacking apprentices. They are payed on a piecework basis and manage to earn good salaries.

STOP 5. Park at the entrance to the Bates Brothers Quarry. Be sure to pull over as far as possible to the side of the road. A small path leads south to the road cut on Route 3.

Exposed at this outcrop are 2 generations of basaltic dikes intruding the "Weymouth granite". Both dikes give evidence of being forcefully intruded into a brittle county rock. Contact metamorphism is minimal to non existent. The first dike is approximately 8' thick and is a multiple intrusion. The initial intrusion was more or less devoid of phenocrysts. The later intrusion, 2' thick, is centrally located in the larger dike and is characterized by large (up to 1" x 1" x 4") white plagioclose phenocrysts set in a dark gray aphanitic matrix. The phenocryst orientation constitutes a well defined flow foliation. In addition, the size sorting and concentration sorting gives evidence of a plug-like velocity profile virtually identical to those found in picritic dikes and sills (Komar, 1972).

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Road Log

Starting point is on abandoned section of Route 1A, 0.2 miles south of Route 495, at entrance to KOA campground on east side of Route 1A in Wrentham. The road cuts at the Route 495 interchange and along Route 1A in the vicinity of the starting point are in the Dedham granodiorite.

On leaving the assembly point we head south on Route 1A. Be careful of traffic southbound on 1A.

Mileage

0.4	Green Street on right. This road leads to the Simeone Aggregate Quarry 0.4 miles to the west.
0.9	Turn right on Cross Street.
1.1	Slow on crest of bridge. Bad bump.
1.3	Take left fork.
1.7	Stop 1. Entrance to Masslite Plant. Our guides will be Mr. Angelo Caperella and Mr. Joe Lorusso. At the conclusion of our visit we will retrace our route to Route 1A.
2.5	Turn right on Route 1A.
3.8	Turn left at traffic light on Route 106 (E. Bacon St.)
4.6	Route 1 intersection. Continue straight ahead on Route 106.
5.4	Route 152 intersection. Continue straight ahead on Route 106.
6.5	Stratified drift on left.
7.2	Morainal material on right.
8.0	Route 495 overpass.
8.8	Route 95 underpass.
9.5	Plant exit on right. Beware of traffic.
8.8	Route 140 intersection. Continue on Route 106.
10.5	Mansfield Center. Continue on Route 106.
12.9	Start climb up bedrock high.
13.0	Exposures on both sides of road are in conglomerate and sandstone beds of the Rhode Island Formation.

13.7   Mansfield-Easton town line.

14.0   Gas storage tank of Brockton-Taunton Gas Company on right.

15.0   Old Mill Pond on left.

15.4   Belcher Division of Dayton Maellable, Inc.

16.0   Route 123 intersection to left. Keep to right (straight ahead)
        on Route 106.

18.7   Hockamock Swamp to left. The ridge we are on is an ice hole deposit.

19.1   Route 138 intersection. Continue straight ahead on Route 106.

20.3   Route 24 overpass. Continue straight ahead on aoute 106.

22.3   West Bridgewater Center. At light take right fork (Route 28) toward
        Bridgewater.

25.0   Bridgewater center - intersection of Routes 18 and 28. Turn right
        and follow Routes 28 and 28 south. Bridgewater green on left.

25.1   Congregational Church on right. Bear left and immediately bear
        right following Route 28 south.

25.2   Bridgewater State College to left. We will return here for lunch.

28.0   Road on left leads to Massachusetts State Correctional Institution
        for the criminally insane. (Of Boston Strangler & Titicut Follies
        fame)

28.8   Taunton River - entering Middleboro.

29.1   Turn left - First Baptist Church on right.

29.5   Turn left at Stiles & Hart sign.

29.7   Taunton River.

30.4   Massachusetts State Correcitonal Institution and Titicut Village.

30.6   Turn right and follow Stiles & Hart signs.

30.7   Turn right on Cook Street.

31.1   Stop 2. Stiles & Hart Brick plant. Bert Andrews, Vice president
        of Stiles & Hart, will be our guide. Following this stop we will
        have a lunch break.

Retrace our route along Cook Street.

31.6   Turn right onto Titicut Street.

31.7   Cross railroad.

32.0   Turn right onto Summer Street.

32.2   Taunton River.

32.4   Turn left onto River Street.

33.3   Note high water table. It is in part perched on the glacio-
        lacustrine silts.

34.2   Stop 3. Kelsey-Ferguson Brick Plant. Mr. D. R. Ferguson, Plant
        Superintendent, will be our guide. Return along River Street to
        Summer Street.

35.0   Turn right onto Summer Street at the junction of River & Summer.

36.2   Taunton River.

36.4   Bear right and remain on Summer Street.

36.5   Till plain cultivated by M.S.C.I. inmates.

40.2   Bear right at fork in road.

40.3   Bear left at island. STOP. DANGEROUS INTERSECTION.

40.5   Bridgewater Center. Continue on through intersection on Route 28.

43.2   West Bridgewater center. Bear left and follow Route 106.

45.4   Exit 30 of Route 24. Bear right & follow Route 24 north.

50.8   Edge of Narragansett Basin. Exposures ahead are of crystalline rock.

53.1   Dedham granodiorite with basalt dike on left. For the next 3.6
        miles there are exposures of Salem gabbrodiorite (dark) and Dedham
        granodiorite (pink) on both sides of the highway. Both formations
        are intruded by dikes ranging in age from Devonian to Triassic.

58.9   Wamsutta formation exposed on right & left. A Pennsylvanian flood-
        plain deposit consisting of sandstone and shale.
        Bear right and follow signs for Route 128 toward Braintree.

59.7   Roadcut on left exposes the "Pondville" conglomerate of Pennsylvanian
       age which nonconformably overlies the Blue Hill granite porphry.
       The Blue Hills are the hills north of the roadcut and parallel
       to the highway.

       The Blue Hills are composed of three main rock units: The Quincy
       granite, the Blue Hills granite porphyry and the Blue Hills
       aporhyolite. According to Chute (1969) the Blue Hills aporhyolite
       is part of the Mattapan volcanic complex. The Quincy granite and
       the Blue Hills porphyry are similar in chemical and mineral compo-
       sition, both being characterized by a high sodium content.

       Field work by Chute and radioactive dating by Bottino and others
       (1970) has established the following age sequence: Blue Hills
       aporhyolite formed in Middle Cambrian followed by intrusion of
       the Quincy granite in Late Devonian or Early Carboniferous and then
       by the intrusion of the Blue Hill porphyry. The Blue Hill porphyry
       is overlain by Pennsylvanian sediments and this provides an upper
       age for the complex.

61.7   Metavolcanic rocks of the Mattapan volcanic complex on left.

62.7   Intersection of Routes 3 and 128. Bear right, follow sign for Route
       3 south. This is a fine example of skeletal topography. The bedrock
       is composed of metamorphic rocks.

67.1   Cloverleaf junction of Routes 3 and 18.

67.5   Glacially polished bedrock (Dedham granodiorite) containing inclusions.

67.7   Stream gauge.

67.9   Rest area. The outcrops west of the rest area are in the Dedham
       granodiorite. The outcrops contain numerous inclusions in various
       stages of assimilation.

68.6   Dikes on left & right. We will visit these dikes on our last stop.

69.0   Weymouth-Hingham line.

69.3   Take exit 29 toward South Hingham-South Weymouth.

70.1   Turn left onto Cushing Street.

70.3   Turn left at traffic light onto Route 53 (northwest).

71.1   Abandoned and active water filled quarries on left and right.
       Stop 4a. Plymouth Quarries, Inc. We will either stop here or at
       4b. depending on conditions on the day of the trip.

71.3   Old building on right was constructed of the"Weymouth granite".

72.0   Stoplight at Lovell's Corner. Turn left onto Pleasant Street.

72.4   House on right constructed of "Weymouth granite".

72.6   Approximately 100' before the Route 3 overpass turn left onto
        gravel road to the Bates Brothers' Quarry. Stop 4b. will be in
        the quarry, about 0.4 miles ahead. Seam-Face Granite Co.

72.9   This is the place we will park our cars for Stop 5. Be sure to pull
        over to the right as far as possible. Stop 5 is down the narrow
        path to the south, a distance of about 100'. at the east end of
        the roadcut.
        From here we will retrace our path to Route 3.

73.2   Turn right onto Pleasant Street.

73.8   Turn right onto Route 53.

75.5   Turn right onto Cushing Street.

76.5   Take entrance ramp to Route 3, northbound.

83.1   On left is site of the first commercial railroad in the United
        States. It was used to transport Quincy granite to barges. The
        granite was then taken to construct the Bunker Hill Monument
        (around 1825). Quincy granite waste piles on left. The topo-
        graphic rise which we are descending marks the southeast edge of
        the Boston Basin. Outcrops on the left are Quincy granite. The
        large excavation on the right is one of the old large quarries in
        the Quincy granite.

86.6   The golf course on the right is on a drumlin.

87.0   Bridge over the Neponset River. A good example of a typical New
        England estuary and tidal marsh.

89.7   Outcrop of Roxbury conglomerate on the right.

91.7   Take exit on left to Massachusetts Avenue. Follow Massachusetts
        Avenue to Kenmore Square and then to Boston University.

                        End of Trip

INDEX TO FIELD TRIP GUIDES AND ARTICLES